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Proceedings of the ARS-SCS Workshop on

HYDRAULICS OF SURFACE IRRIGATION

with participation by
State Agricultural
Experiment Stations and
Land-Grant Colleges

Denver, Colorado
February 9-10, 1960

Agricultural Research Service
UNITED STATES DEPARTMENT OF AGRICULTURE

FOREWORD

Surface irrigation systems have been used for thousands of years. Rapid development of irrigation in this century has created a need for procedures and criteria to design surface irrigation systems. Early studies to develop usable relationships between stream size, shape and size of border or basin, slope, intake rate, rate of advance, storage in noncapillary space and on the surface of the soil are evidenced by publications in this country in 1913 and 1932, and in Russia in 1930.

Later studies included the same variables but also considered stream recession on graded borders, hydraulic resistance to flow by the crop cover and soil surface roughness, erosion aspects, water surface profile as the irrigation stream advances, shape of the channels, and intake rates that are not constant. Studies such as these generally involve analysis of data obtained by observing current irrigation practices or when conducting field trials to evaluate or refine previously established relationships.

The hydraulics of flow in surface irrigation systems is extremely complex; therefore, has essentially been neglected for many years. Irrigation engineers in the Soil Conservation Service have been requested to design increasing numbers of irrigation systems. Because of a lack of information on surface hydraulics, they have been forced to develop and use empirical relationships to design these systems.

A number of research projects have been initiated during the past 5 years using analytical approaches, laboratory flumes or models and field studies to determine the relationships involved in the hydraulics of surface irrigation systems. In some instances projects have just been initiated recently and only limited data obtained. Considerably more data are expected in the next 5 years.

This workshop was held for several reasons: (a) to bring to attention of research engineers the current empirical procedures being used by design engineers with emphasis on procedures that need improvement; (b) to acquaint the design engineers with research underway and to provide them with recent data or relationships that may be incorporated into present design procedures; (c) to provide an opportunity for design and research engineers to discuss mutual problems; and (d) to provide research engineers an opportunity to discuss their research projects.

A major portion of the current research being conducted in the United States on hydraulics of surface irrigation systems is represented in the papers published in these proceedings. Most of these projects are underway; therefore, final results and interpretations may not be available at the present time.

We hope these papers will contribute to a better understanding of problems encountered in the design of surface irrigation systems.

MARVIN E. JENSEN
Western Soil and Water Management Research Branch
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BORDER IRRIGATION

PRESENT PROCEDURES AND MAJOR PROBLEMS IN BORDER IRRIGATION DESIGN [1]

by

Dell G. Shockley [2]

INTRODUCTION

Before the problems associated with the design of border irrigation systems are discussed, it might be helpful to define and describe this method of irrigation. It is a controlled surface flooding method of irrigation water application. The field to be irrigated is divided into strips separated by parallel dikes or "border ridges", and each strip is irrigated separately. Water is introduced at one end of the strip and progressively covers the entire strip. When considered in these general terms, one definition will cover all border irrigation. However, all border irrigation is not alike. When water application principles are taken into account, three different kinds of border irrigation must be considered.

DEFINITIONS

Level Border

This is a ponding method of water application. The border strips have no slope in the direction of irrigation, and they are closed at the ends so the water will be retained until it infiltrates into the soil. Stream sizes used are not critical as long as they are sufficient to provide coverage of the entire strip in a relatively small proportion of the time required to put the desired amount of water into the soil. The generally accepted design criterion is complete coverage in one-fourth of the required infiltration time.

Graded Border

This is a balanced advance-recession method of water application. The border strips have some slope in the direction of irrigation, and the ends usually are not closed. Each strip is irrigated by turning in a stream of water at the upper end. The stream must be the size needed to cover the entire strip length in about the time required to complete the irrigation at the upper end of the strip. When the advancing waterfront nears the lower end of the border strip, the stream is turned off. The water temporarily stored on the ground surface then moves on down the strip and percolates into the soil to complete the irrigation. Uniform and efficient application of water with the graded border method is dependent upon the use of irrigation streams of the proper size. Too large a stream will result in inadequate irrigation at the upper end of the strip or in excessive surface runoff. If the stream is too small, the lower end of the strip will be inadequately irrigated or the upper end will have excessive deep percolation.

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Guide Border

This is a type of border irrigation that has not been well recognized. In fact, it has no accepted name. The "guide border" designation is a tentative proposal of the Soil Conservation Service.

In the guide-border method of irrigation, water is turned into the upper end of a sloping border strip and allowed to run until a sufficient amount of water has infiltrated into the soil. The balanced advance-recession principle of water application does not apply. Water is applied as in furrows, using a large initial stream to provide adequate spreading over the strip. After the water reaches the lower end of the strip, the irrigating stream may be cut back to reduce surface runoff. This method of irrigation is used where the unit-stream required for a balanced advance-recession type of graded border irrigation provides insufficient flow depth to insure adequate spread over the strip. This condition can be expected on steep slopes and/or on soils having low intake rates.

PRESENT DESIGN PROCEDURE

Unit-Stream Approach

Present border design procedures are empirical. It is assumed that irrigation stream size is directly proportional to border strip area. This is the unit-stream concept presented in Agriculture Handbook No. 82.[3/] Under this assumption, once the proper unit-stream has been determined for a given slope, soil, and depth of application, the actual irrigating stream for any set of border strip dimensions is merely the product of the unit-stream and the number of unit areas in the strip. A unit area in this case is considered to be 100 square feet, and a unit-stream is the stream required for a border strip area 1 foot wide and 100 feet long.

Agriculture Handbook No. 82 presents a family of curves as a guide for the selection of unit-streams for various depths of water application, different basic intake rates, and a border strip irrigation grade of 0.5 percent. This Handbook also provides correction factors for use in adjusting unit-streams to slopes other than 0.5 percent. These curves have been widely used,

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3/ Criddle, W. D., Davis, S., Pair, C. H., and Shockley, D. G. Methods for evaluating irrigation systems. U. S. Depart. Agr., Agriculture Handbook No. 82, 1956.

and in most cases have resulted in reasonably satisfactory designs. However, experience has shown some areas of weakness and a need for some revision. Irrigation engineers from the Soil Conservation Service are now working on a revised set of curves. These new curves are based on studies of typical soil intake characteristics and, therefore, can be considered to be a rational development. They indicate the unit-stream required to deliver a given depth of application to a unit area in the time required for that depth to infiltrate into the soil. On gentle slopes, unit-streams must be increased to allow for the lag in start of recession. Correction factors for this time lag are being developed. Usually the correction will not be significant on slopes over about 0.5 percent.

The unit-streams developed, as explained above, are the unit-streams required for application at 100 percent efficiency. They must be empirically adjusted for the expected level of field application efficiency. The general formula for the computation of unit-streams for any given soil is:

$$q = \frac{1}{E}\left(\frac{T}{T - T_L}\right)\frac{F}{7.2\,T}$$

where

q = Unit-stream in c.f.s.

E = Efficiency expressed as a decimal

F = Desired depth of water application in inches

T = Time, in minutes, required for the infiltration of F inches of water

T_L = Recession time lag in minutes (from the time the stream is cut off until recession begins)

Design Example

Since the revised unit-stream curves have not been completed, the curves shown in Agriculture Handbook No. 82 will be considered as representing present design procedure. Starting with these curves, a design problem can be illustrated by the following example.

Assume:

A border irrigation design is needed for the irrigation of alfalfa and small grain on a site having the following characteristics:

Field slope is 1.0 percent.

Basic soil intake rate is 1.0 inch per hour.

Normal irrigation application is 3.0 inches.

Maximum allowable flow depth is 0.4 foot.

Find:

The required unit-stream.

The maximum allowable length of run.

The time required to apply an irrigation.

Unit-Stream

From Handbook No. 82 (figure 15)

q for a 0.5 percent slope = 0.01 c.f.s.

slope factor for 1.0 percent slope = 0.86

design q = 0.01 x 0.86 = 0.0086 c.f.s.

Maximum Length of Run

The maximum length of run can be determined by dividing the allowable stream size per foot of border strip width by the required unit-stream.

The allowable irrigating stream is limited by the hazard of erosion or by the allowable flow depth.

From Handbook No. 82 (table 3) the maximum nonerosive stream per foot of strip width is $0.06/S^{0.75}$ c.f.s., or for an irrigation grade of 1.0 percent is 0.06 c.f.s.

From Manning's formula, using an "n" value of 0.150, the stream required to produce a flow depth of 0.4 foot would be 0.22 c.f.s.

Therefore, erosion is the limiting factor, and the maximum irrigating stream per foot of strip width is 0.06 c.f.s.

The maximum length of run, then, will be 0.06/0.0086 = 7.0 hundred feet.

Time Required

The time required for an irrigation is the time needed to deliver the volume of water represented by the desired depth of application, adjusted for the expected efficiency level. The time (T) in hours can be computed from the formula:

$$T = \frac{d}{432\ Eq}$$

where

d = required net depth of application in inches

E = expected efficiency level. For this example, assume 0.70.

q = design unit-stream in c.f.s.

The time required will be

$$\frac{3.0}{432 \times 0.70 \times 0.0086} = \underline{1.15 \text{ hours}}$$

Other Design Criteria

Slope Limitation

If, in the above example, the field slope had been less than 0.4 percent, the length of run would have been limited by the permissible depth of flow. The tabulation below shows the effect of slope and allowable depth of flow on length of run.

Slope	Unit-stream 0.5 percent slope	Slope factor	Design q	Max. Unit-width stream 0.4 ft.depth	Max. Unit-width stream Nonerosive	Max. Length
Percent	c.f.s.		c.f.s.	c.f.s.	c.f.s.	Feet
0.0	0.01	2.00	0.0200	0.060	---	300
.1	.01	1.43	.0143	.069	---	480
.2	.01	1.23	.0123	.096	---	780
.3	.01	1.13	.0113	.120	0.150	1060
.4	.01	1.04	.0104	.140	.120	1150[1]
.5	.01	1.00	.0100	.155	.100	1000[1]

[1] Limited by erosion hazard.

Minimum Depth of Flow Limitation

If, in the design example, the basic intake rate of the soil had been less than 0.5 inch per hour, the stream size required for a balanced advance-recession type of irrigation would have been too small to spread across the border strip. In this case the design would be based on the guide border method of water application. The criterion now used to define the minimum unit-stream for graded border irrigation is as follows:

$$q \text{ (minimum)} = 0.004\ S^{0.5}$$

where

S is the irrigation slope in percent

With a basic soil intake rate of 0.3 inch per hour, the unit-stream for a 0.5 percent slope would be 0.003 c.f.s. The slope factor for a 1.0 percent slope is 0.86, so the design unit-stream would be 0.0026 c.f.s. This is less than the minimum of 0.004 c.f.s. needed for a 1.0 percent slope.

The guide border design would be based on the use of an initial unit-stream of 0.004 c.f.s. The maximum length of run would be 0.06 (erosion limitation) divided by 0.004, or 1,500 feet.

The time to complete an irrigation would be the time required for 3.0 inches of water to infiltrate into the soil. The time can be approximated by using the time formula given in the design example and the unit-stream as computed for graded border irrigation.

$$T = \frac{3.0}{432 \times 0.65 \times 0.0026} = 4.1 \text{ hours}$$

The 65 percent efficiency used in the above computation is based on the assumption of well leveled border strips and a reduction of flow after water reaches the lower end of the run.

SUMMARY AND CONCLUSIONS

Border designs are based on the unit-stream concept in which it is assumed that irrigating streams are proportional to the border strip area. It is assumed also that rates of advance are in direct proportion to stream sizes. This is an empirical approach. Stream sizes required to satisfy soil intake characteristics can be developed on a rational basis, but flow characteristics are not known.

Before a rational design procedure can be developed, the basic hydraulic characteristics of small streams of water flowing over permeable soil must be known. Procedures for estimating rates of advance and rates of recession are needed. Factors that should be studied include such things as slope, channel roughness, channel shape, stream size, and soil intake characteristics. Erosion limitations also need further study.

ATTEMPTS AT IMPROVEMENT OF DESIGN PROCEDURES FOR BORDER IRRIGATION[1]

by

L. F. Lawhon [2]

INTRODUCTION

Mr. Shockley pointed out some definite gaps in the present empirical procedures. Although the attempts we have made in improving these procedures are still empirical in nature, we think they may approach rational solutions provided the assumptions we have made can be proven.

ASSUMPTIONS

General assumptions are made in regard to hydraulics of surface irrigation. These are:

1. The irrigation stream must be large enough to satisfy intake in the area covered or having opportunity for intake.
2. The flow may be characterized as steady nonuniform flow. (Observations indicate that flow is turbulent rather than laminar. Some indications have been observed that an unsteady condition exists near the leading edge when the irrigation stream is considerably in excess of the intake requirements -- however, this effect diminishes as velocity of advance decreases.)
3. The rate of advance is in proportion to the amount the irrigation stream is in excess of intake requirements.
4. With a given channel shape, irrigation grade, and retardance characteristic, the rate of advance can be related to a stream size by use of Manning's formula for flow in open channels.

By these assumptions, we have been using the following criteria for design and evaluation of border irrigation systems in the plains areas of Oklahoma, New Mexico, and Texas.

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[1] Contribution from the Soil Conservation Service, U. S. Department of Agriculture.

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NOMENCLATURE

The following nomenclature is used in the Southern Plains area:

F = Accumulated intake in inches at time T_c.

F_N = Net irrigation application in inches.

D_G = Gross irrigation application in inches.

E = Design efficiency in percent.

I_b = Identification of design intake curve.

I_a = Average or design intake rate for field application of F inches.

S = Border slope in percent.

s_o = Border slope in feet per foot.

s_1 = Hydraulic slope in feet per foot.

L = Length of run in feet.

L_A = Length of advance in feet.

$L_{(min)}$ = Minimum desirable length of run in feet.

$L_{(max)}$ = Maximum desirable length of run in feet.

W = Border ridge spacing in feet.

T = Time of application in minutes.

T_c = Clock time.

T_o = Opportunity time for intake in minutes.

T_A = Time of advance in minutes.

T_L = Time recession starts after time T in minutes.

Q = Border stream in c.f.s.

$\frac{Q}{w}$ = Border stream in c.f.s. per foot of border width.

Q_v = Average rate of surface storage per foot of border width for any time T_A.

d_1 = Depth of flow at Station 0+00 on border (at turnout).

n = Coefficient of roughness in Manning's formula.

DESIGN

The following formulas are used to design border irrigation systems:

$$T = (T_o \text{ for } F_N - T_L) \tag{1}$$

$$L = 60T_o \left(\frac{1.486}{n}\right)^{0.6} (Q_v)^{0.4} (s_1)^{0.3} \tag{2}$$

where $T_o = T_o$ for F_N

$$Q_v = \frac{Q}{w} - \frac{F_N L}{720 T_o} = \frac{Q}{w} - \frac{I_a L}{43200}$$

$$s_1 = \left(\frac{d_1}{L} + s_o\right)$$

$$d_1 = \frac{\left(\frac{Q}{w}\right)^{0.6}}{\left(\frac{1.486}{n}\right)^{0.6} (s_1)^{0.3}}$$

NOTE: If $s_o < 0.0005$ or $\cong 0$.

$$d_1 = 0.833(n)^{0.46} \left(\frac{Q}{w}\right)^{0.46} (L)^{0.23}$$

If $s_o > 0.0005$ and L is over 1000 d_1

$$s_1 \cong s_o$$

$$L_{(min)} = 60T_o \left(\frac{1.486}{n}\right)^{0.6} \left(\frac{F_N}{7.2T_o}\right)^{0.4} (s_o)^{0.3} \tag{3}$$

$$L_{(max)} = 60T_o \left(\frac{1.486}{n}\right) \left(\frac{F_N}{12}\right)^{0.67} (s_o)^{0.5} \tag{4}$$

$$T_L = \frac{\frac{(d_1)^2}{2s_o}}{\frac{Q}{w}} = \frac{\left(\frac{Q}{w}\right)^{0.2}}{2\left(\frac{1.486}{n}\right)^{1.2} (s_o)^{1.6}} \tag{5}$$

$$\frac{Q}{w} = \frac{F_N L}{720 T_o} + Q_v = \frac{I_a L}{43200} + Q_v \qquad (6)$$

$$E = \frac{F_N}{D_G} = \frac{F_N}{\left(\frac{Q}{w}\right)\left(\frac{T}{L}\right)(720)} \qquad (7)$$

where all points receive F_N or more.

EVALUATION

The following formulas are used when evaluating border irrigation systems:

$$F = \left[\left(\frac{Q}{w}\right)\left(\frac{T_A}{L_A}\right) - (Q_v)\ \frac{T_A}{L_A}\right] 720 \quad \text{when } T_o = T_A \qquad (1)$$

$$T_o = T_c \text{ of recession} - T_c \text{ of advance} \qquad (2)$$

$$L_A = 60 T_A \left(\frac{1.486}{n}\right)^{0.6} (Q_v)^{0.4} (s_1)^{0.3} \qquad (3)$$

$$\text{or} \quad Q_v = \left[\frac{L_A}{60 T_A \left(\frac{1.486}{n}\right)^{0.6} (s_1)^{0.3}}\right]^{2.5}$$

$$s_1 = \frac{d_1}{L_A} + s_o \qquad (4)$$

$$E = \frac{F_N}{D_G} = \frac{F_N}{\left(\frac{Q}{w}\right)\left(\frac{T}{L}\right)(720)} \qquad (5)$$

where all points receive F_N or more.

WATER SURFACE CONFIGURATION AND VELOCITY OF ADVANCE IN HYDRAULIC LABORATORY TESTS[1]

by

D. L. Bassett and E. R. Tinney[2]

INTRODUCTION

This report is prepared in order that persons interested in the improvement of irrigation through better understanding of it can become aware of the work underway at Washington State University in irrigation hydraulics. This is a progress report only. It contains brief descriptions of the WSU project and certain conclusions which appear valid at this time. Data reported herein are confined to the flow of water over a smooth concrete surface with zero infiltration for purposes of certain hydraulic analysis. Empirical relationships are presented for such value as they may have in illuminating the real functions involved. These preliminary findings are of considerable importance in future investigations but are not expected to have field application at this time.

THE PROJECT

The objective of the project as now constituted is to establish engineering criteria for the design of low gradient irrigation systems by:

(a) determining the hydraulic phenomena involved, and then
(b) developing design criteria from the hydraulic relationships.

All effort so far has been confined to subobjective (a). The work is currently being done under a memorandum of agreement between the WSU Department of Agricultural Engineering and the Division of Industrial Research with active support of personnel in the Department of Mathematics. The work is financed by both State and Federal funds (WRR - W-65). A separate but related WSU study of the hydrodynamics of such flow is currently being financed by the National Science Foundation.

The general procedure being used involves definitions of the several hydraulic phenomena under controlled laboratory conditions. At the conclusion of these tests, it is anticipated that field evaluations will be necessary which will in turn permit irrigation system design criteria to be developed. Facilities available for the work include a tilting flume, 3 feet wide and 69 feet long. In addition to usual water control and measurement facilities, the flume is equipped to record water depth photographically, and to permit manual recording of velocity of the advancing water front. Original equipment to simulate infiltration of water from the flume is completed but has not been used in tests reported here.

---

[1] Contribution from the Washington Agricultural Experiment Station, Scientific Paper No. 1955. Work was conducted under Project No. 1317.

[2] Assistant Professor and Assistant Agricultural Engineer, Department of Agricultural Engineering; and Head of Allbrook Hydraulic Laboratory; Washington State University, Pullman, Washington, respectively.

For orderly investigation the irrigation process has been divided into three phases:

(a) advance of water across the surface,
(b) development and depletion of surface storage, and
(c) recession of water from the land surface.

All work thus far has been confined to phase (a). Preliminary tests to aid in the development of mathematical models have been conducted under the following conditions:

- Five stream sizes - (0.1, 0.2, 0.3, 0.4, and 0.5 c.f.s.).
- Five slopes - (0.0, 0.1, 0.25, 0.5, and 1.0 percent).
- Three degrees of channel roughness - (smooth concrete,
  3/8" - 3/4" expanded metal, and
  3/8" - 3/4" crushed rock).

Only analyses of the tests on concrete are given since they present a unique opportunity to make certain initial verifications. Selected results regarding water surface configuration and velocity of advance are presented below.

CURRENT RESULTS

Water Depth

Water surface shapes for a distance of 50 feet behind the advancing front on the concrete surface are contained in figures 1, 2, and 3. These data illustrate the relative influence on depth of stream size, channel roughness, and channel slope. Figure 4 is a logarithmic plot of similar data.

One of the early hypotheses advanced in this study provides that the flow regime can be considered to exist in two parts: (a) an initial transient section which gradually leads to (b) a section of essentially steady state flow. This hypothesis is now considered confirmed by data shown in figure 4. It will be observed that depth continues to change throughout the test length of the flume for low slopes, confirming the presence of a transient and changing flow situation. The existence of essentially steady state flow is

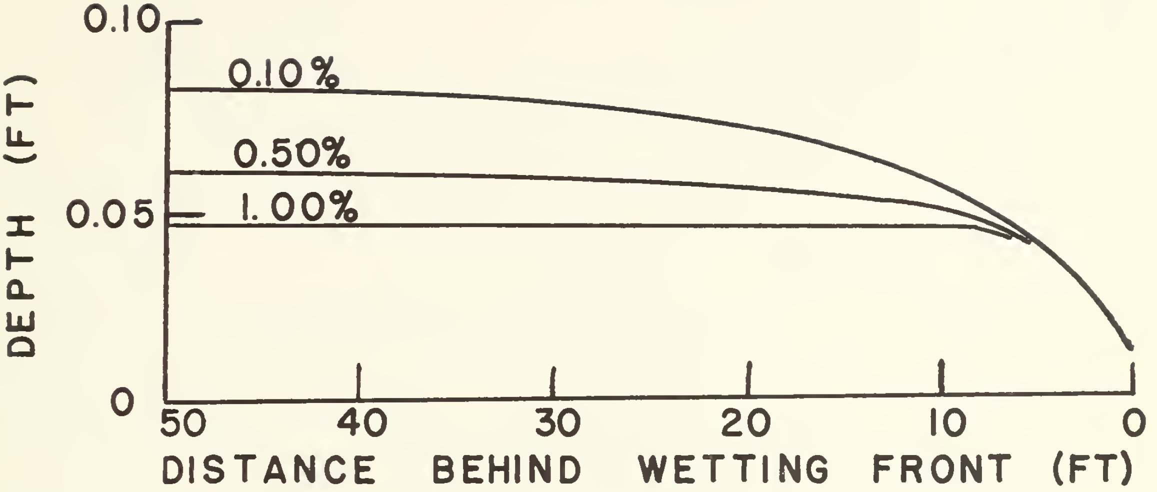

Figure 1.--Water depth as influenced by channel slope. Concrete surface, Q = 0.3 c.f.s.

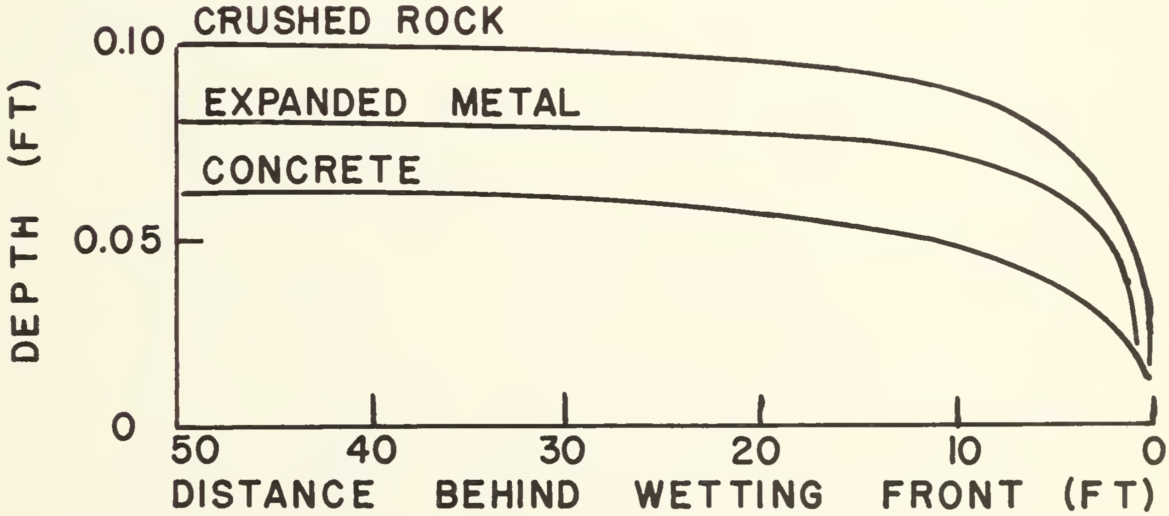

Figure 2.--Water depth as influenced by channel roughness. Q = 0.3 c.f.s. S = 0.5 percent.

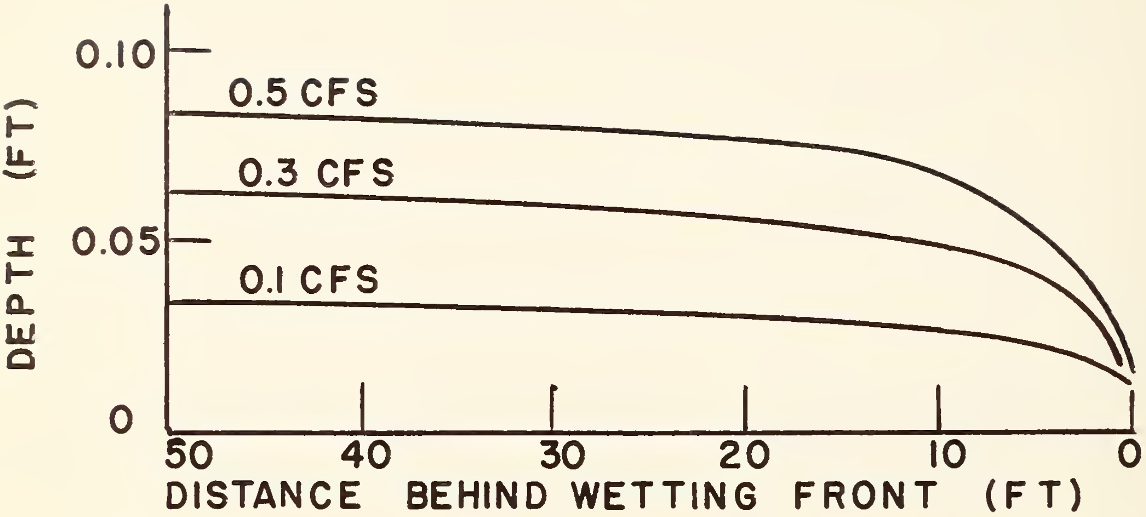

Figure 3.--Water depth as influenced by discharge rate.
Concrete surface, S = 0.5 percent.

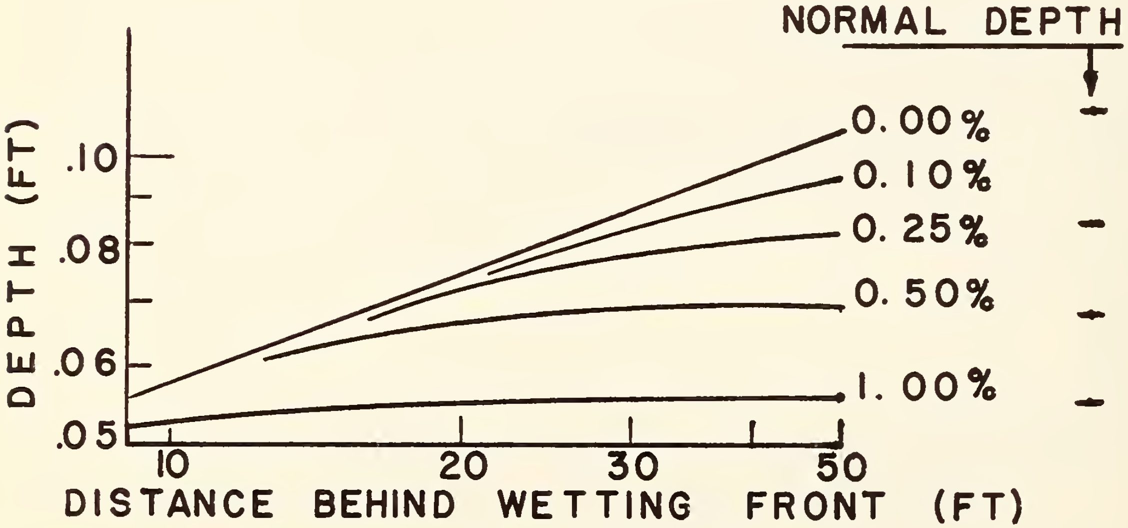

Figure 4.--Comparison of observed and normal depths.
Concrete surface, Q = 0.4 c.f.s.

suggested by the constant depths which are attained on steeper slopes. The presence of both flow conditions and the transition between as shown in figure 4 tend to confirm the above hypothesis.

It was further theorized that where depth approaches a constant value, that value will be normal depth, d_n. Normal depth for the several flow conditions represented is also contained in figure 4. It will be observed that for steep slopes where depth is approaching constancy in the test length of the flume, the normal depth is approached (within limits of experimental error). On the flatter slopes a distance of greater than 50 feet is required for normal depth to be attained. This evidence is currently accepted as confirmation of the hypothesis that normal depth as computed by Manning's equation will be approached.

The test data for 0.2, 0.3, and 0.4 c.f.s. stream sizes were analyzed to yield an empirical equation describing water depth. Based on the above conclusions, the general expression below is considered logical.

$$d = d_n \left(1 - Ae^{-Bu}\right) \qquad (1)$$

where d is the actual water depth

d_n is the normal depth for the given conditions

e is the base of the natural logarithm

u is a function of the several variables involved, and

A and B are constants.

If d_n is expressed in terms of unit-stream size, channel roughness and slope, and A and B are evaluated, the following expression results

$$d = \left(\frac{qn}{1.486s^{0.5}}\right)^{0.6} \left(1 - \frac{0.515}{e^{22.9xs}}\right) \qquad (2)$$

where q is the unit-stream size in c.f.s.

x is the distance behind the advancing front in feet, and

s is the channel slope in feet per foot.

Normal depth must be determined by trial and error from known "n" relationships. This expression does not hold for very short distances behind the front. Depths so computed approximate (plus or minus 4 percent) the observed values for arbitrarily chosen test conditions.

Internal properties of the flowing water are not considered variables in these tests, but are assumed constant since water temperature remained between 60 and 65° F. during most of the tests. It will be observed from equation (2) that the magnitude of normal depths in a given channel is determined by stream size, channel roughness and slope. For distances greater than a few feet behind the front, the manner in which normal depth is approached in a given channel is affected by distance and slope but is essentially independent of stream size in the tests thus far accomplished.

Velocity of Advance

The velocity of advancing front is measured throughout the flume length by recording on a sequence timer the instant water reaches each 2-foot station. The nature of the advance velocity is illustrated in figure 5.

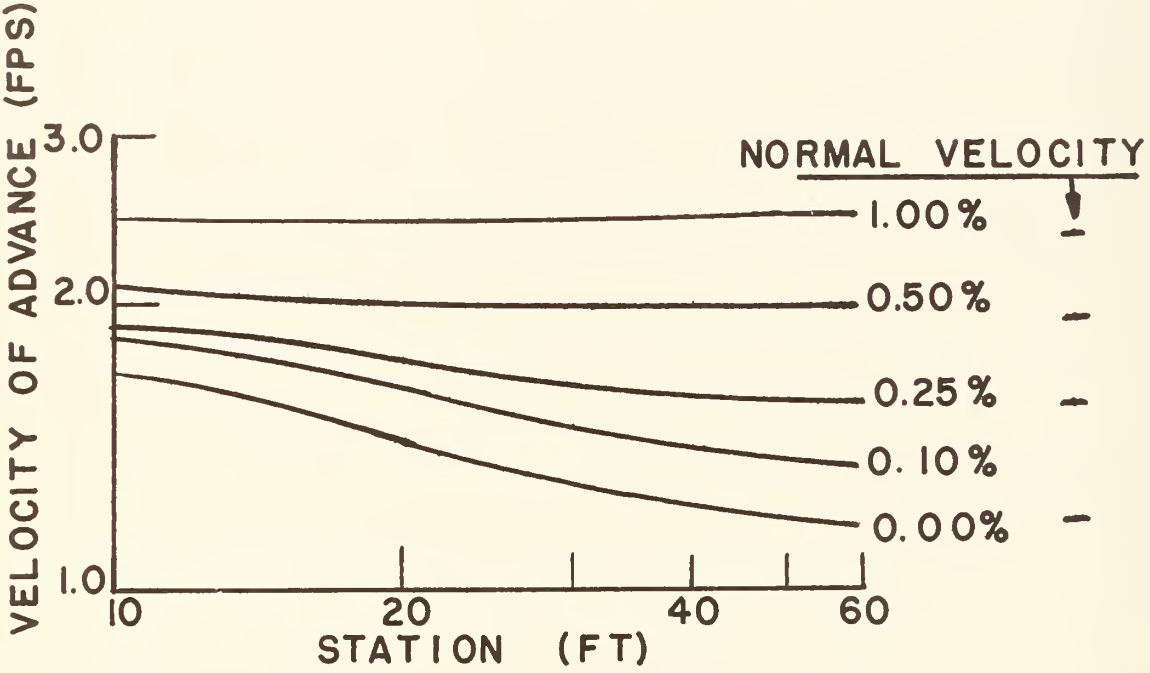

Figure 5.--Velocity of advance of water. Concrete surface, Q = 0.4 c.f.s.

Entrance conditions have a marked influence on velocity in the upper reaches of the flume. After entrance conditions are overcome and channel characteristics control the flow, velocity tends to approach some constant value in much the same manner as did water depth. In fact, it can be shown that when depth approaches constancy, the velocity of advance will at about that time also approach constancy, suggesting an interdependence between the two.

A corollary hypothesis to those mentioned above provides that if depth becomes constant, then advance velocity must also become constant. Further, if the constant depth is normal depth, then the constant velocity will be normal velocity, or stream size divided by normal area. The tendency for normal velocity to be approached is indicated in figure 6. Figure 6 indicates that the advance velocity and the average velocity in steady flow are equal. The hypothesis is therefore currently accepted.

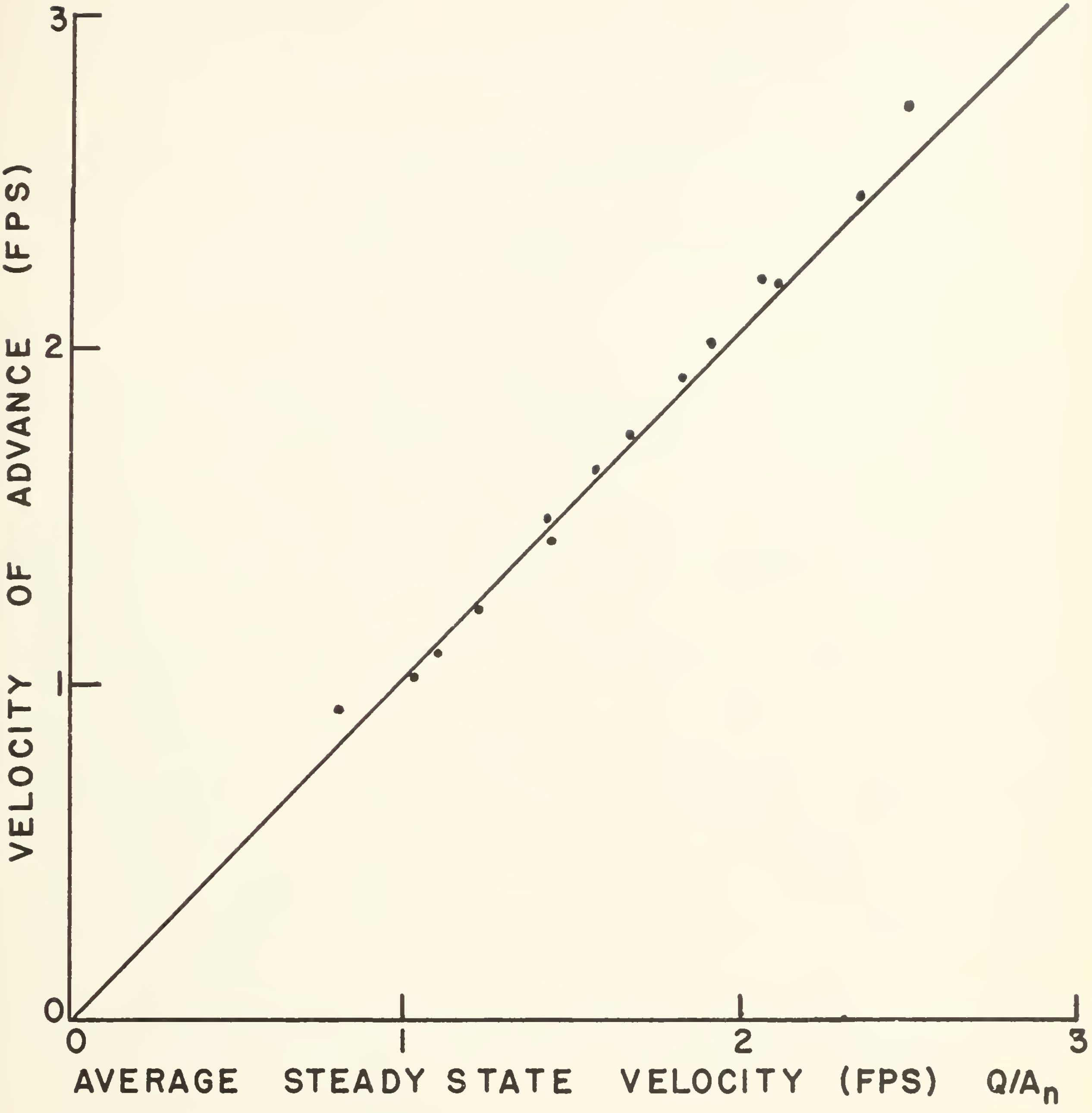

Figure 6.--Comparison of velocity of advance with average steady state velocity. Concrete surface, all tests where $D = D_n$.

An expression similar to equation (2) describing velocity is currently under development but is not available at the time of this writing.

CONCLUSIONS

The test program with zero infiltration reported herein supports acceptance of the following conclusions:

1. An advancing stream of water flowing over an impermeable bed can be considered as consisting of two phases:

   (a) an initial section of unsteady, nonuniform flow which is gradually transformed to
   (b) an essentially steady state flow for slopes greater than zero.

2. Normal depth is approached by the flowing water.

3. The development of depth follows certain laws which can be approximated empirically as in equation (2). This expression can be used also to determine how far behind the front essentially steady state flow occurs.

4. Velocity of the advancing front approaches constancy in somewhat the same manner as does depth and approaches the average velocity in the steady flow region behind the front.

The authors wish to re-emphasize the preliminary nature of work described herein and acknowledge the probability of refinement as additional information is assembled.

HYDRAULICS OF SURFACE IRRIGATION 1/

by

James A. Bondurant 2/

The design of surface irrigation systems is, at the present time, dependent on empirical relationships and procedures. The theoretical relationships between the variables involved in surface irrigation have never been

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1/ Contribution from Soil and Water Conservation Research Division, Agricultural Research Service, U. S. Department of Agriculture, and Idaho Agricultural Experiment Station, cooperating.

2/ Agricultural Engineer, Western Soil and Water Management Research Branch, Soil and Water Conservation Research Division, Agricultural Research Service, U. S. Department of Agriculture, Boise, Idaho.

determined so that surface irrigation systems can be designed on a rational basis. The basic hydraulic relationships which exist when a variable intake rate, such as that exhibited by most soils, is imposed on open channel flow have never been determined. Proper design of surface irrigation systems will be obtained only when we have a clear, concise understanding of the effects of the variables involved in surface irrigation. This paper briefly summarizes a study on hydraulics of surface irrigation underway at Boise, Idaho.

The objective of the study being conducted at Boise is to improve the design and operation of surface irrigation systems. This objective is to be accomplished by: (a) Determining, by model study, the relationships between the variables involved in surface irrigation; (b) correlation of findings from the model study with results obtained from field studies; and (c) formulation of methods and procedures for use of these relationships for design of surface irrigation systems.

The flow of water advancing or receding in a surface irrigation system is a nonuniform, unsteady flow phenomenon. It is neither uniform along its profile nor does it remain the same at any given point, but changes with time. This is the effect of imposing a variable intake rate on open channel flow. This flow phenomenon is the cumulative effect of several variables whose separate effects need to be determined and then expressed quantitatively for design purposes. Some of the variables involved are soil surface slope, intake rate, rate of water application, surface roughness, and effect of channel shape on velocity distribution. Most of these variables can be studied by models simulating this type of flow. The theoretical relationships developed from model studies will need to be correlated with and adapted to field conditions.

The study is based on simulation of open channel flow by use of a Hele-Shaw viscous fluid model. The Hele-Shaw model gives irrotational (essentially two dimensional) flow such as would occur in the center of a uniform border strip. Also, since flow in a Hele-Shaw viscous fluid model is potential flow, the flow pattern and flow relationships obtained with this model may therefore be considered as basic flow pattern and relationships. Adaptation of these flow patterns and relationships to flow of water in furrows should be possible by addition of a shape factor to the variables being studied for simulation of border flow.

Consideration of the problem indicates that the following variables are involved:

q	Flow rate per unit width	L^2/T
x	Advance distance	L
T	Time from beginning of test	T
I	Cumulative intake from beginning of test	L

ν	Kinematic viscosity	L^2/T
C	Roughness (Chezy's)	$\sqrt{L}/T$
g	Acceleration of gravity	L/T^2
S	Slope	L/L

The Hele-Shaw model consists of two closely spaced parallel glass plates forming a narrow channel through which the viscous fluid flows. Intake is simulated by using compressed fiberglass filter material in the lower one-half of the flume. Slope is varied by tilting the flume. The flow pattern is recorded photographically by a 35 mm. camera at various intervals of advance distance. Negatives are developed and then projected full scale and copied on cross-section paper. The data are then obtained by measurement. The elapsed time is recorded on the photograph, also.

Flow patterns were obtained for four flow rates on five slopes. Flow rates were in an approximate geometric progression; 1, 2, 4, and 8. Slopes were 0, 1/2, 1, 5, and 10 percent.

The data are being analyzed by dimensional analysis methods. Considering the following variables flow rate, slope, intake, time, advance distance, viscosity, dimensional analysis indicates the functional equation:

$$\frac{x}{I} = \left(f \; \frac{q}{\sqrt{gI^3}} \; , \; \frac{T}{\sqrt{I/g}} \; , \; \frac{C}{\sqrt{g}} \; , \; \frac{\nu}{\sqrt{gI^3}} \; , \; S \right)$$

Since six parameters cannot be plotted on one graph, some must be combined. By taking logarithms of the parametric values multiple regression analysis can be used to give a power equation relating the parameters. This analysis is not complete at this time.

A new, improved Hele-Shaw model has been constructed. With this model more accurate advance data will be obtained. The stream recession function will be studied also. The model is also equipped so that dye may be injected to better define the flow pattern.

Field plots having slopes of 0, 1/2, 1, and 2 percent are being constructed. These will be used to obtain field data which can be correlated and adapted to the analyses developed from the model study. Roughness effects will also be studied on these plots.

MANNING'S EQUATION FOR SHALLOW FLOW[1]

by

Charles C. Bowman [2]

INTRODUCTION

Manning's equation can be used for calculating the velocities of shallow water movement over grassy strips with careful selection of "n" values. Previous studies by Vernon J. Palmer, W. O. Ree, and others show the Manning equation has been accepted, with reservations, by many research workers for shallow movement of water. There are others who believe the thin, low velocity flows are laminar in nature and Manning's equation should not be used under these conditions.

The objective of this study is to determine the type or types of flow existing when a thin sheet of water is flowing at low velocities through vegetative growth and to determine the best velocity equation for these conditions.

PROCEDURE

Laboratory Studies

A flume was built with clear plastic sides giving a clear view vertically and horizontally of the fluid flow. The bottom of the flume was made of laminated wood, smoothed and finished to give a minimum value for "n". A stilling basin was installed at the inlet giving a smooth, steady flow. Two dye injectors were installed, each injector being placed in from their respective sides one-third the distance across the flume. (See figure 1). The flume was built so a variation in slope could be made. Combs representing vegetative growth of various densities were attached to a standard equipped with strain gages for direct measurement of the induced drag. Density of growth is expressed as percent of cross-sectional area occupied by comb stems.

Reynolds' number (N_R) equals $\frac{d \rho V}{\mu}$ where (d) is the average diameter of the grass stems. N_R is directly proportional to the diameter. The comb stems and velocity are directly responsible for the vortices or turbulence formed. The velocity under these conditions is the average velocity of the flow. In this manner N_R is a direct measure or indicator of the existing conditions.

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[1] Contribution from Montana Agricultural Experiment Station.

[2] Agricultural Engineer, Agricultural Engineering Department, Montana State College, Bozeman, Mont.

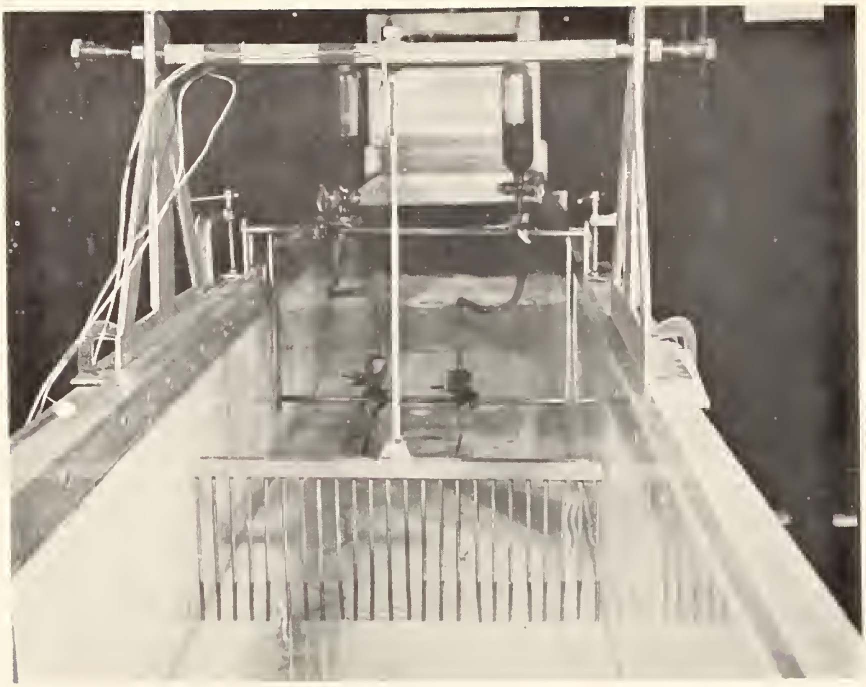

Figure 1.--Flume showing dye injectors and comb.

Field Studies

Border strips were used to derive new "n" values to be used in Manning's equation. The borders were 18 feet wide and 300 feet long with a slope of 0.0112. The borders were covered with a second-year crop of alfalfa, alfalfa-grass, and grass.

Predetermined quantities of water were applied to each border strip. Measurements of depth of flow, velocities (using dye), and density of growth were made. The flows were measured by two methods. The first method used required a broad crested weir. The second method used employed three Parshall flumes spaced at equal intervals across the border. The flumes were connected by canvas dams which formed a solid dam between flumes and across the border. Each flume was installed so that the entrance was level with the ground. This gave a minimum ponding effect without submergence. The canvas dams extended forward to form an apron. The apron allowed for the measurement of flow from any section of vegetation with an accuracy of ± 1 percent of the normal accuracy of the flumes.

The densities of the vegetation were determined by measuring the diameters of the vegetative stems and making a count of the stems per unit area. The area used was 1 inch of width by 1 foot of length. The following equation was then used to find the percent of area occupied by vegetation in a finite area one-tenth of an inch in width and 1 foot long.

$$\frac{\text{Average diameter of stems in inches} \times \text{Total number of stems per unit area}}{120} = \text{Percent of finite area covered by vegetation.}$$

RESULTS OF LABORATORY STUDIES

Laminar flows were established at flume slopes of 0.00, 0.005, 0.01, and 0.015 foot per foot and at varied depths. (See figure 2.)

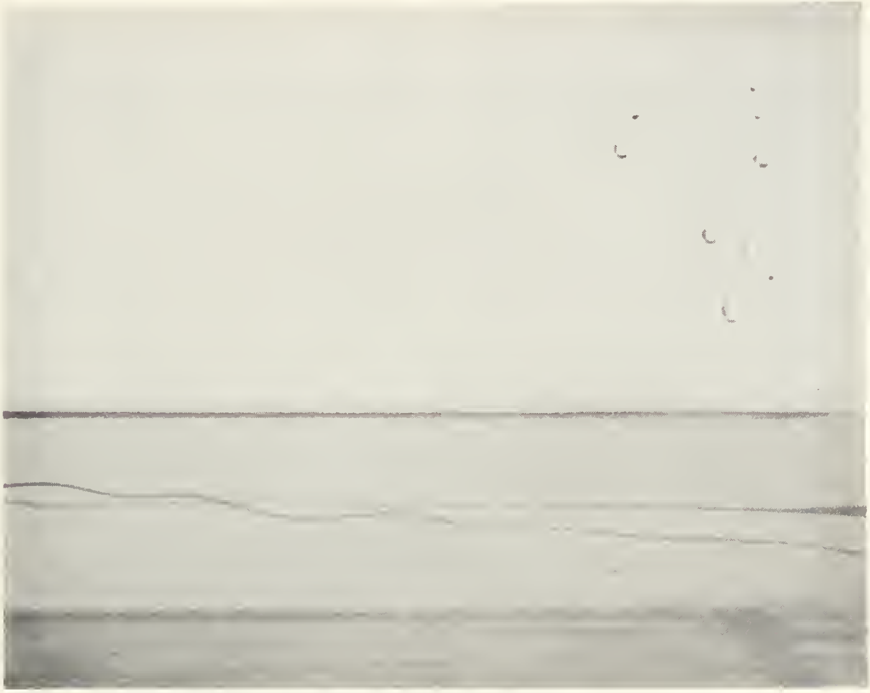

Figure 2.--Laminar dye stream.

When combs representing vegetative growth of various densities were inserted into one of the laminar dye streams, vortices formed at velocities as low as 0.035 f.p.s. and a Reynolds number of 29.5. The vortices continue to form and turbulence results as long as the simulated vegetative growth exists. This occurred with a wide range of vegetative densities. When a single row of vegetation with a density of 20 percent exists, the vortices form immediately due to the drag of the vegetation. The flow returns to a laminar condition upon leaving the vegetative row. Large diameter stems are more effective in causing vortices than the small diameter stems at the same densities.

Vennard[3] stated that vortices will be formed separately and very weakly at N_R of 10 and strong vortices at N_R of 1000. The author found strong vortices formed at N_R of 29.5 and at velocities of 0.035 f.p.s. This velocity is well below the velocities encountered in the field.

When small pebbles, sand, or a rough surface are placed on the smooth bottom ahead of the dye injectors, a transitional boundary layer is introduced with vertical vortices similar to those formed behind the vegetative growth. The pebbles, sand, and rough surfaces will not create turbulence alone, but results in turbulence when combined with the vegetative growth.

By the use of the two dye streams in a smooth flume, it is possible to show a turbulent and a laminar stream side by side in the same flow. (See figure 3.) Whenever a meandering flow exists through clumps of simulated vegetation, it is possible to have a combination of flows. Turbulence will exist through and around the clumps while a laminar flow will exist between the clumps. If debris exists, such as stems, between the clumps of vegetation, the largest portion of the meandering flow is turbulent, a portion is in transition, and a portion is laminar. These conditions are dependent on the spacing of the clumps. The closer the clumps, the more turbulent the flow.

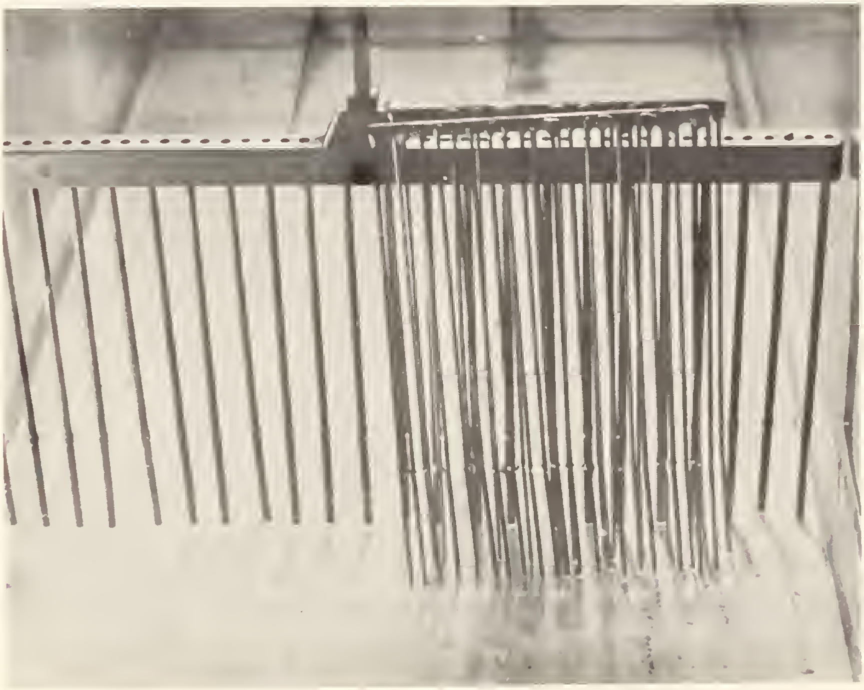

Figure 3.--Laminar and turbulent dye stream.

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[3] Vennard, Elementary fluid mechanics, 3rd ed., p. 351.

TENTATIVE PRACTICAL APPLICATIONS

The drag induced by the vegetation within a shallow flow is directly proportional to the density of the vegetation and depth of flow. The velocity increases with an increase in depth of flow. The drag induced by the velocity is directly proportional to the square of the velocity.

By using the product of the velocity and the depth of flow (VD) and the ratio of the density to the depth of flow (d/D) a relationship is developed which identifies the conditions that exist in the field. By plotting the "n" values as found from the measured velocities through the vegetation as the ordinate and the product of the velocity and the depth of flow as the abscissa, a line is developed which can be identified by the density-depth ratio. (See figure 4.) It is difficult to use this figure to find the true velocity that exists within the field. However, by using Manning's equation to determine a theoretical velocity (V_t) where the depth of desired flow, slope of the field, and a fixed "n" value of 0.025 is used to determine V_tD, it becomes a simple procedure to find the corrected "n" value and the true velocity for any field. (See figure 5.)

Example

A border strip will safely hold a depth (D) of 3 inches of water. It has a 1 percent slope (S) and a 5 percent density (d) of growth. Find the true velocity (V) of the flow.

First step: Find the theoretical velocity.

$$V_t = \frac{1.486\ (D)^{2/3}\ (S)^{1/2}}{0.025}$$

$$= \frac{1.486 \times (0.25)^{2/3}\ (0.01)^{1/2}}{0.025} = 2.35 \text{ f.p.s.}$$

Second step: Find V_tD and d/D.

$$V_tD = 2.35 \times 0.25 = 0.588$$

$$d/D = \frac{0.05}{0.25} = 0.2$$

Third step: Refer to figure 5 and find the intersection of the lines d/D = 0.2, and $V_tD = 0.588$. The new "n" value is 0.061.

Fourth step: Use the new "n" value in place of the 0.025 "n" value in the first step and solve for the true velocity of flow.

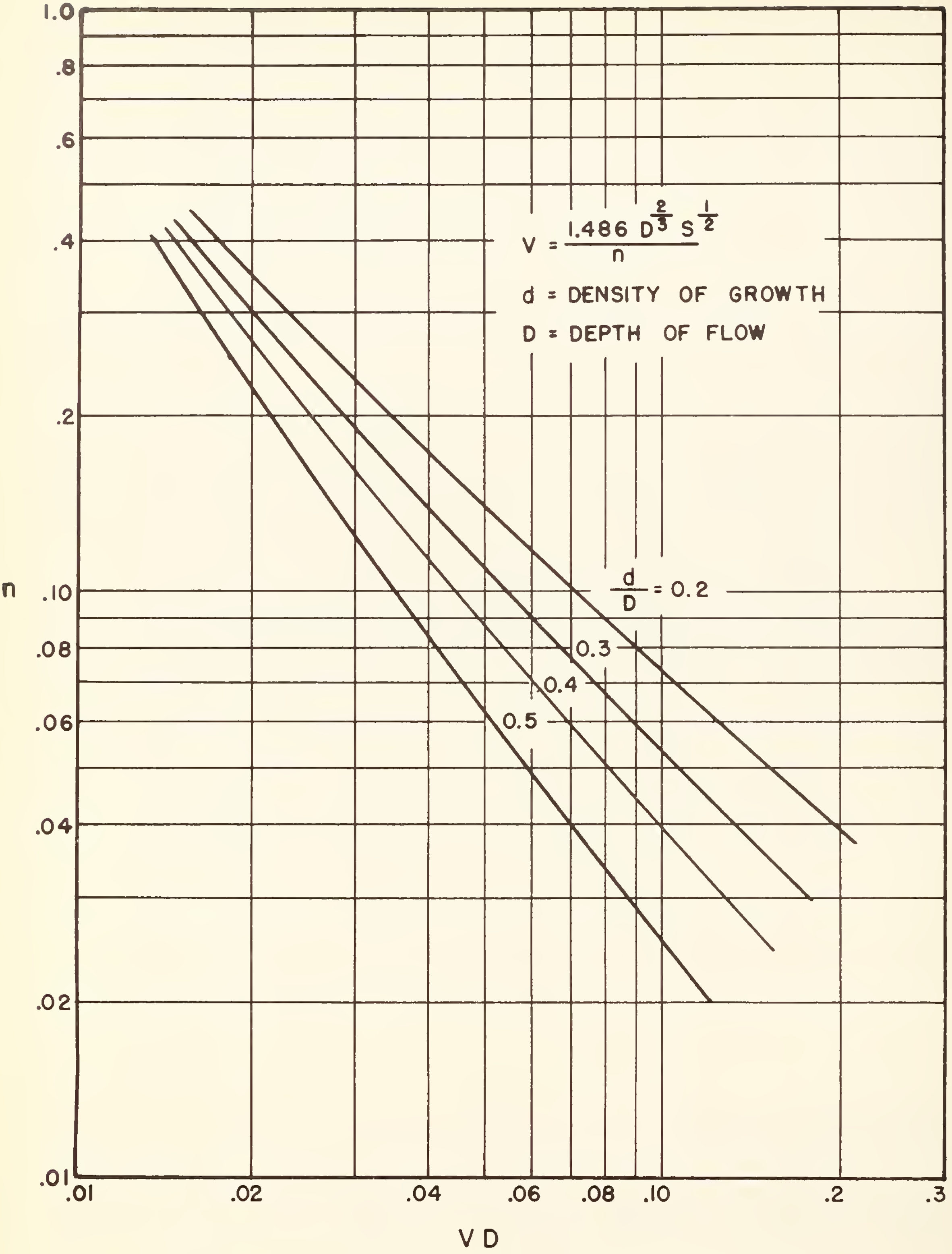

Figure 4.--Relationship of new "n" to the product of theoretical velocity x depth.

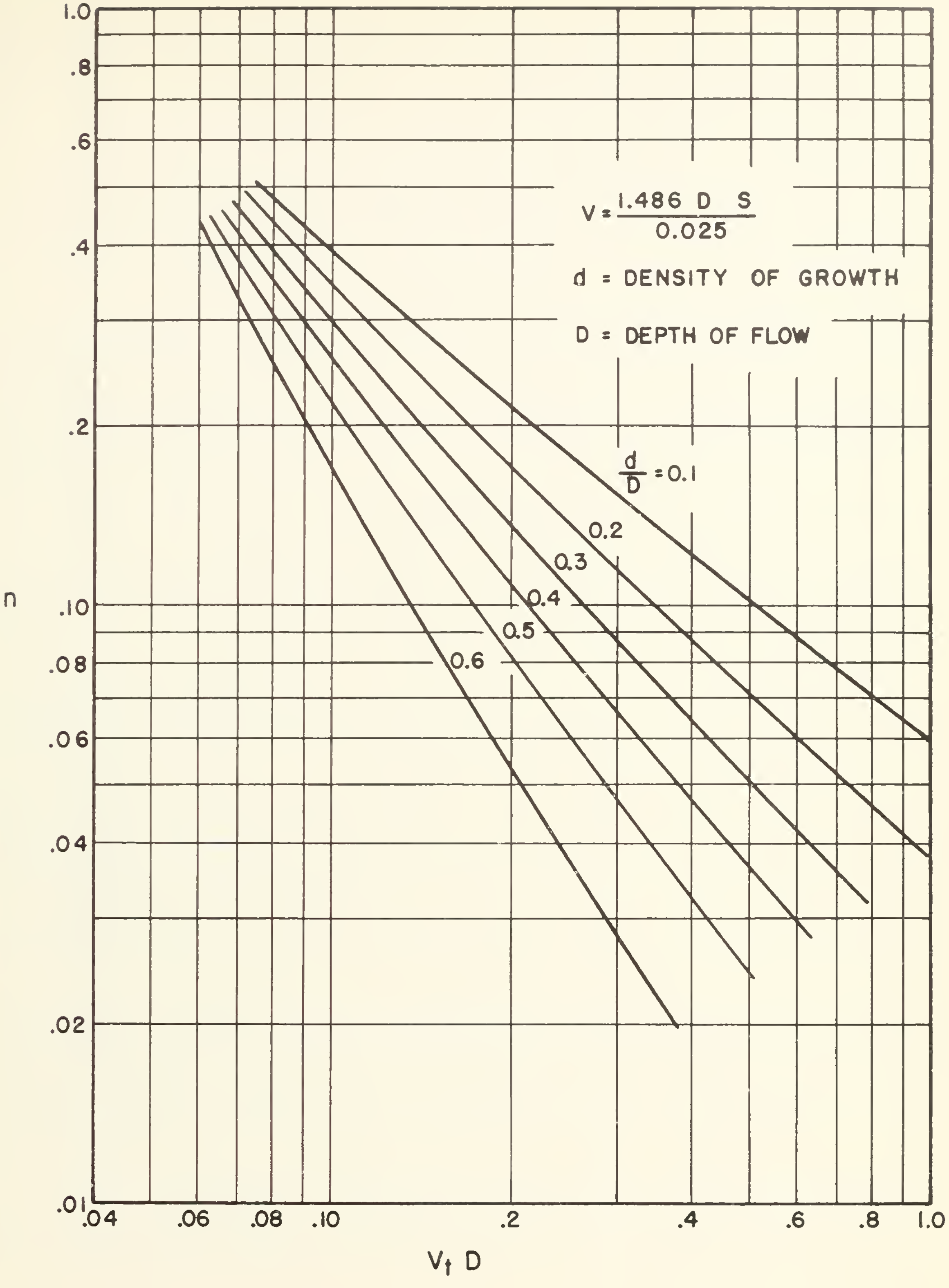

Figure 5.--Relationship of "n" to the product of velocity x depth.

$$\text{True Velocity} = \frac{1.486\ (D)^{2/3}(S)^{1/2}}{"n"}$$

$$= \frac{1.486\ (0.25)^{2/3}\ (0.01)^{1/2}}{0.061} = 0.964 \text{ f.p.s.}$$

To solve for the rate of flow (Q) for a given border strip, use the following equation:

$$Q = (1-d)DWV$$

Given: $D = 0.25$ foot

$d = 0.05$

$W = 1.00$ foot

$$Q = (1-.05)\ (0.25)\ (1)\ (0.964)$$

$$= 0.229 \text{ c.f.s. maximum per foot of width.}$$

CONCLUSION

The shallow flow of irrigation water through vegetation is turbulent or in a transitional state. Shallow flows through scattered clumps of vegetation can be a combination of turbulent and laminar flow.

Manning's equation can be used in all cases when careful selection of "n" values is made. The proper "n" values can be found by using the relationship of the product of the theoretical velocity and depth of flow and the ratio of the density of the growth and depth of flow. The theoretical velocity is found by using a constant "n" value of 0.025. The new "n" value, when used with the depth of flow and slope of the border, should give a more accurate flow velocity.

More field data must be collected to refine present curves in the lower range of "n" values and to establish lower d/D ratio lines. It should be pointed out the above procedure and use of curves must be limited to theoretical design until such time that the accuracy of the curves has been proven.

MATHEMATICAL RELATIONSHIPS EXPRESSING THE HYDRAULICS OF SURFACE IRRIGATION [1]

by

Vaughn E. Hansen [2]

INTRODUCTION

The hydraulics of surface irrigation is a complex subject and, consequently, not well understood. Nevertheless, good irrigation design depends upon understanding its principles. The variables involved and their significance have been pointed out previously by the author [3]. However, these factors will be summarized herein as the basis for the more detailed discussion to follow.

VARIABLES INVOLVED

Figure 1 shows a schematic view of border irrigation, illustrating the basic variables involved in the hydraulics of surface irrigation. They are as follows:

1. Size of stream
2. Rate of advance
3. Length of run and time required
4. Depth of flow
5. Intake rate
6. Slope of land surface
7. Surface roughness
8. Erosion hazard
9. Shape of flow channel
10. Depth of water to be applied

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[1] Contribution from Utah State University, Logan, Utah. This paper describes developments by seven contributors, working somewhat as a team to solve this complicated problem. Since none of the results have been published except the author's initial paper and since much of the development is tentative, the author is not able to include herein all that has been tentatively developed. However, trends and the nature of progress are shown.

[2] Professor of Civil and Irrigation Engineering and Director, Engineering Experiment Station, Utah State University, Logan, Utah.

[3] Hansen, Vaughn E. "The Importance of Hydraulics of Surface Irrigation", Paper 1788, Journal of the Irrigation and Drainage Division, Proceedings of the American Society of Civil Engineers (September 1958).

It should be clearly remembered that the hydraulics of surface irrigation has all the complexities of unsteady open channel flow plus the added major complication of a variable intake. Hence, direct solution of this complex problem is not simple.

TWO APPROACHES

Two approaches to the problem have been made somewhat simultaneously at Utah State University. The first is a hydrodynamic approach made by Loo and Hansen 4/ with subsequent development by Yu-Si Fok 5/. In this study the configuration of the free surface is of particular interest and an expression for the rate of advance is being developed. The fundamental differential equation, describing the shape of the free surface, has been developed by Loo and Hansen. Solutions obtained from the equation have been compared to field data and have been found to check reasonably well. Fok's efforts toward integration of the differential equation look promising.

The second approach to a mathematical expression for the hydraulics of surface irrigation has been made by Christiansen, Bishop, and Fok 6/ based upon earlier development by Fok 7/, followed by a subsequent development by Fred W. Keifer, Jr. 8/. Herein, the intake characteristics have been related to the rate of advance without attempting to define the free surface. By knowing the intake rate, the rate of advance can be predicted; or by measuring the rate of advance, the intake rate can be calculated.

Hydrodynamic Approach

In the hydrodynamic approach 9/ the emphasis is placed upon the shape of the free surface. The variables used are shown in figure 2. The assumptions are as follows:

1. Inflow, q_o, is constant.
2. Momentum of the infiltration outflow is neglected.
3. Width of the border is constant and is sufficiently wide that side effects can be neglected.

4/ Loo, Harry Huan-yen, and Hansen, Vaughn E., Hydraulics of Unsteady Open Flow over a Porous Bed, publication pending.

5/ Graduate student, Civil and Irrigation Department, Utah State University, Logan, Utah.

6/ Christiansen, J. E., Bishop, A. A., and Fok, Yu-Si, The Intake Rate As Related to the Advance of Water in Surface Irrigation. Presented at the 1959 Winter Meetings of the American Society of Agricultural Engineers, Chicago, Ill.

7/ Fok, Yu-Si, Formulas for the Determination of the Proper Length of Farms, Taiwan Water Conservancy, Taipei, Taiwan. Series 6, Vol. 3 (September 1, 1958).

8/ Assistant Professor, Civil and Irrigation Engineering Department, Utah State University, Logan, Utah.

9/ The following is a brief summary of the development cited in footnote number 4. The detailed mathematical developments are too involved to present more than the types of developments undertaken and the results obtained. Nomenclature used in the original paper will be followed.

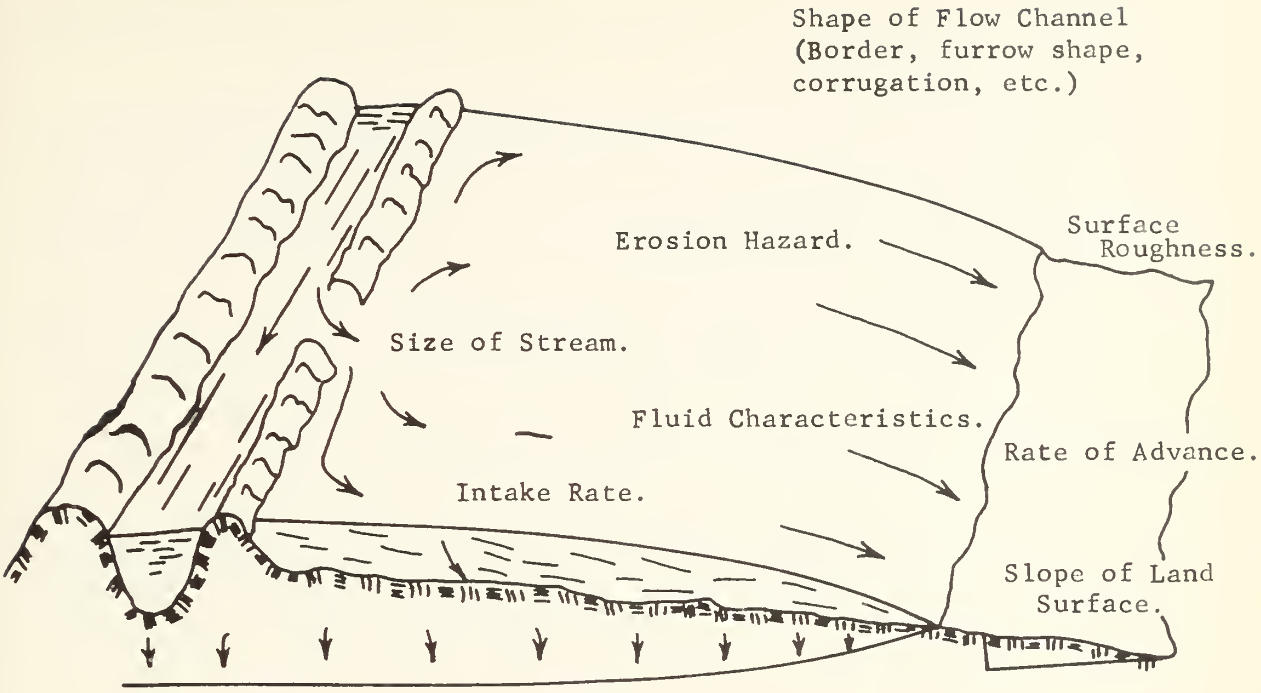

Figure 1.--Schematic view of border irrigation illustrating the basic variables involved in the hydraulics of surface irrigation.

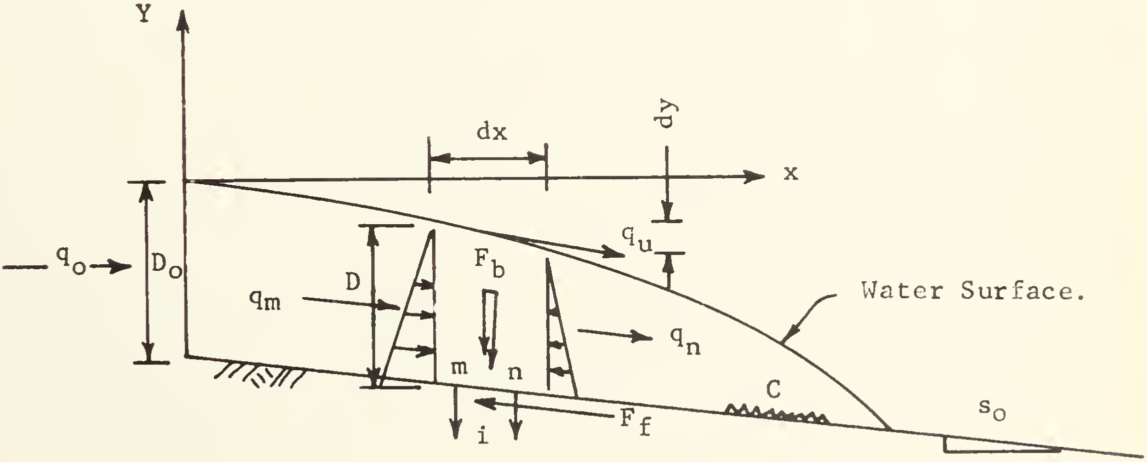

Figure 2.--Surface profile of water advancing over sand surface, showing the variables used in the hydrodynamic analysis.

4. Slope of the border is uniform.
5. Depth of flow, D_o, at the upstream end is constant and is the normal depth for the given discharge, q_o, ground slope, so, and Chezy's roughness coefficient, C.
6. The resistance coefficient, calculated for uniform flow at a given depth and mean velocity, applies to the nonuniform, unsteady flow.

By the application of the momentum principle to a section of flow, dx, as shown in figure 2, the following equation is obtained:

$$\frac{dy}{dx} = \frac{1}{gD}\left(\frac{gv^2}{C^2} - vi - q\,\frac{dv}{dx}\right) \tag{1}$$

To facilitate the integration of equation (1), dy and dv have been expressed in terms of dq and dD with the result that:

$$\left(D - \frac{v^2}{g}\right) dD = - \frac{vi}{g}\, dx - \frac{v}{g}\, dq \tag{2}$$

and

$$\left(D - \frac{v^2}{g}\right) dD = - \frac{v^2 i}{g}\, dt - \frac{v}{g}\, dq \tag{3}$$

To simplify the solution of equation (3) by computers, the following dimensionless form was used:

$$\left(\frac{\Delta D^2}{D}\right) - G\left(\frac{\Delta D}{D}\right) - H = 0 \tag{4}$$

where

$$G = 2 - \frac{\Delta Z}{D} \tag{5}$$

$$H = 4\,\frac{V^2}{gD}\,\frac{i\Delta t}{D} \tag{6}$$

Field data for the surface profiles are not available to compare with the surface predicted by equation (4). However, rate of advance data are available from USDA research at Eden, Wyoming10/. Hence, a family of curves of surface profile was calculated using equation (4) from which rate of advance has been determined. Depths of flow and discharges for the two tests used for comparison with the equation were measured only at station 2 + 00. Consequently, the roughness coefficient C could be evaluated only if this section was assumed constant throughout the border strip.

10/ Anonymous. Progress Report on Irrigation Investigations for Eden Valley, Wyoming, Irrigation Project. SCS and ARS, USDA, December 6, 1957.

The calculated time to reach station 6 + 00 is 14 percent less than the measured value in one case and 8 percent more in the other case.

Subsequent development by Fok gives promise of a solution to the differential equation (4) which will describe the shape of the free surface. With the shape of the free surface defined, the rate of advance probably can be analytically expressed to yield practical formulas describing the hydraulics of surface irrigation.

Similar analysis is planned for the recession functions. When the techniques of analysis have been determined for the advance functions, the recession characteristics will not be difficult to evaluate.

Intake Related to Rate of Advance

A direct approach to relating intake rate to rate of advance of the water over the land, not necessarily involving the shape of the free surface, has been made by Christiansen, Bishop, and Fok[11]. They assumed the average depth of water on the surface remained constant.

Three forms of the intake equation have been considered.

$$I = K\,t^n \qquad (7)$$

$$I = C + K\,t^n \qquad (8)$$

$$I = A + Be^{-rt} \qquad (9)$$

Equation (7) was found to be sufficiently accurate for a short period of irrigation, and equation (8) represents the longer irrigations. The complexity of equation (9) makes it less practical.

The accumulative depth of water applied, D, is obtained by integrating these equations. Fok has obtained the average depth applied by integrating the accumulative depth equation and dividing by the time.

Integrating the accumulative depth equation in this manner over various times corresponding to operating conditions yields values of average depth applied to given operating conditions. From these equations, the percent loss, P, in deep percolation can be evaluated. An expression derived after simplifying the more complex equation[12] is:

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[11] See footnote 6 for reference to this work. Only a summary will be presented herein. Nomenclature used in the original paper will be followed.

[12] Credit for suggesting equation (10) is due Jaswant Singh, graduate student from India attending Utah State University.

$$P = \frac{100\ (n + 1)}{2\ R + 1} \qquad (10)$$

where

$$R = \frac{t_2}{t_1}\ , \qquad (11)$$

with the time of arrival at the end of the run being t_1 and the time water is applied to the lower end of the run being t_2.

The time required, t, for a given depth of water, D, to enter the soil is found by solving for t after integrating equation (7).

$$t = \frac{D\ (n + 1)}{k}^{\frac{1}{n+1}} \qquad (12)$$

The length of run, L, in time, t, is found to be:

$$L = \frac{qt}{D_a + D_s} = \frac{qt}{\frac{kt^{n+1}}{(n+1)\ (n+2)} + D_s} \qquad (13)$$

where D_s is the equivalent average depth of water on the surface, or the average cross-sectional area divided by the spacing of furrows or borders.

Solving the equation with data from Criddle,et al.[13] for a case where 3.75 inches of irrigation water were applied, the computed time of application was 17.0 hours compared to a measured time of 16.5 hours. Other data yielded a calculated application of 7.65 inches compared to a measured amount of 8.26 inches. Another trial gave 4.88 inches calculated compared to 4.91 inches measured.

Using the same data, the calculated percent losses were 47.8 percent compared to a measured value of 51.2 percent, and from trial two a calculation of 18.5 percent compared with 18.0 percent measured. Hence, it is seen that the approach of Christiansen, Bishop, and Fok produces results which compare well with field data.

OTHER RESEARCH PENDING

Complimentary research is underway by Keifer, Fok, and Singh, which will extend the results that have been discussed. Keifer has pointed out that

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[13] Criddle, Wayne D., Davis, Sterling, Pair, Claude H., and Shockley, Dell G. Methods for evaluating irrigation systems. U. S. Department of Agriculture, Agriculture Handbook No. 82, 1956, Soil Conservation Service.

Christiansen, Bishop, and Fok have derived an approximate average absorbed depth that is correct only if the rate of advance is constant. However, if the correct rate of advance is used, a truer value of average absorbed depth can be obtained, and the error involved can be reduced. Keifer's approach is to use an empirical expression for the length of advance in a given time, which is confirmed by available field data. This assumed equation is being used to develop equations paralleling those by Christiansen, et al.

To more accurately define the rate of advance, Fok is using the equation of the free surface developed by Loo and Hansen. If the rate of advance can be defined, or the empirical equation developed by Keifer confirmed, the techniques developed by the other investigators can be utilized for deriving practical expressions.

Singh's work is directed toward a better expression for intake which will define the variables influencing the constants used in the intake equations. When this is accomplished, a measurement taken at a given time can be extrapolated to other field conditions with reasonable confidence.

SUMMARY

Contributions to the mathematics of the hydraulics of surface irrigation have been made by seven investigators, independently and collectively, at Utah State University. Somewhat independent approaches have been taken which appear to be leading to a common answer. The results are merging into complimentary components where the answers obtained by one group are leading to better solutions for all components of the problem. Unfortunately, these developments are not sufficiently advanced to permit the results to be integrated within this presentation. However, it is encouraging that useful results can be expected shortly. Major breakthroughs have been made in the complicated mathematics of the hydraulics of surface irrigation.

CONCEPTS ON DESIGN OF BORDER IRRIGATION SYSTEMS [1]

by

John R. Davis [2]

INTRODUCTION

The design of a border irrigation system implies that maximum effort has been expended to specify those variables within the control of the designer and operator to result in the optimum performance of the system. Usually, however, the criteria for evaluating the performance of irrigation systems are restricted to only those for which precise information is available; thus the "design" is usually related to a performance parameter that only vaguely resembles the optimum performance. Specifically, border systems are presently "designed" to result in the application of sufficient water with as little over-irrigation or under-irrigation as possible. We are forced to relegate to the background such factors as labor efficiency, crop growth or production efficiency, minimum operating costs and changes in economic structures, and general optimization of overall water resources.

The design of a border system is certainly complicated. In view of the lack of data concerning some of the above factors and their interactions, we introduce a compromise by selecting only a few objectives upon which to base performance criteria. In addition, because the predictions of the behavior of the system are far from perfection, most border systems are "built" by using the evaluation of previously constructed systems under the same or similar conditions. Certainly, empirical designs leave much to be desired but are an effective means of initiating a fairly competent design.

The objectives of a border irrigation system must be outlined before the system is designed. That is, the system should be designed either to produce maximum economic returns or to distribute the desired amount of water as efficiently as possible to the field. In some cases these objectives will coincide; in others, meeting both of these objectives will be impossible. Other objectives include necessary leaching of accumulated salts, minimum soil erosion, minimum leaching of valuable nutrients, and prevention of drainage or compaction problems. The point to make here is that one must choose the most desirable objective first in the design and then attempt to meet the other objectives through manipulation of the variables affecting the performance of the system. Obviously, as far as the farmer is concerned, the objective of producing the maximum economic returns is the most desirable; and this objective is the one upon which the engineer should base an evaluation.

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[1] Contribution from California Agricultural Experiment Station, University of California, Davis, Calif.

[2] Lecturer and Associate Specialist, Department of Irrigation, University of California, Davis, Calif.

FACTORS INFLUENCING SYSTEM BEHAVIOR

Regardless of the objectives of the border irrigation system, one must be able to predict the behavior of the system. For example, present designs require knowledge of the rate of advance, the rate of recession, the infiltration characteristics of the soil, the rooting depth and water use rates of the crop, and the leaching requirements. These data allow the engineer to select the combination of physical factors to achieve the most uniform irrigation for the desired application of water. These data will also allow the engineer to reach the optimum economic irrigation, if the economic data are available.

The time is approaching, however, when border systems can be designed from prior knowledge of soil, topography, land use, etc.; without the expensive and time-consuming method of field evaluations to which we have resorted. Considerable progress has been made on the predictions of the rate of advance of the waterfront by Lewis and Milne [3], Hall [4], and Ostromechki [5]. Hall's equation illustrates the factors influencing this rate of advance phenomenon:

$$\Delta X_i = \frac{\frac{Q \Delta t}{b} - (a_i \Delta X_1 + a_{i-1} \Delta X_2 + \cdots + a_2 \Delta X_{i-1})}{k y_1 + c d_\circ + e}$$

where Q/b represents the flow rate into the border per unit width; the a's and y_1 represent the infiltration characteristics; $d_\circ$ represents the water depth on the surface of the border and is a function of the surface slope, flow rate, and hydraulic roughness; and e represents the possible unevenness of the soil surface. Recently, researchers have concentrated their efforts on the factors affecting $d_\circ$; that is, the hydraulics of shallow flow over or through various forms of rough surfaces, with the primary objective of improving upon the accuracy of such predicting equations.

Similar efforts are being made for predicting the rate of recession in borders. Further refinements are also necessary for predicting the advance in a border after the flow is turned off and for predicting recession with and without advance.

Of considerable importance also is the ability to accurately describe the infiltration phenomena. Recent efforts on the mechanics of flow from cylinder infiltrometers are certainly justified, and of perhaps greater importance is the need for describing a field intake rate which considers such effects as the gopher holes and cracks. A proposal by Christiansen, et al.[6] is a good step in this direction.

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[3] Lewis, M. R., and W. E. Milne. Analysis of border irrigation. Agr. Engr. 19:267-272. 1938.

[4] Hall, W. A. Estimating irrigation border flow. Agr. Engr. 37:263-265. 1956.

[5] Ostromechki, Jerzy. On the computation of check flooding irrigation. Gospodarka Wodna, XIII: 93-98, 133-136. 1953. Translated from Polish.

If the predicting equations mentioned prove successful, a good evaluation or design procedure might then involve the following steps:

(a) Determine field grade, length of border, and soil type.
(b) With a given Q, determine rate of advance, depth of flow, and rate of recession.
(c) From rate of advance and recession data, determine the infiltration characteristics, hydraulic roughness characteristics, and the rates of advance and recession for other lengths of border, other grades, and other flow rates.
(d) Select the most desirable combination of grade, flow rate, and length to achieve the desired objective.

The last two steps are involved and expensive with a slide rule but could be fully realized with the use of electronic computers. This has already been achieved to some extent by Hall.

The final objective must still be chosen, however, and at this point the decision rests upon many considerations. This paper proposes to illustrate several methods whereby various objectives can be reached.

DESIGN OF BORDER SYSTEMS

Present methods of design are based upon field evaluations and have been discussed elsewhere, Criddle and Davis [7]. Following are several other methods that might be employed to successfully attain a desired objective.

First Method

Presume that the objective is to irrigate a border with 100 percent efficiency, applying a desired depth of water over the entire length of the border. Known are the depth of water to apply, erosion hazards, and infiltration characteristics of the soil.

If no water is lost by deep percolation or tailwater, then

$$V_a = dwL = Qt \tag{1}$$

where V_a is the volume applied, d is the desired depth of application, w and L are the length and width of the border, Q is the flow rate and t is the total time that water flows into the border. If Q is expressed in c.f.s., t in minutes, d in inches and w and L in feet, the equation is as follows:

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[6] Christiansen, J. E., Bishop, A. A., and Fok, Yu-Si. The intake rate as related to the advance of water in surface irrigation. Presented at the 1959 Winter Meetings of the American Society of Agricultural Engineers, Chicago, Ill.

[7] Criddle, Wayne D., and Sterling Davis. A method for evaluating border irrigation layouts. (Provisional) U. S. Department of Agriculture, Soil Conservation Service. March 1951.

$$dwL = 720\ Qt \qquad (2)$$

To avoid any underirrigation or overirrigation at the upper end of the border, t is the time when the depth d has been reached. If a total infiltration function $d = at^m$ can be assumed, then equation (2) becomes

$$d^{1-\frac{1}{m}}\ wL\ a^{\frac{1}{m}} = 720\ Q \qquad (3)$$

For example, suppose $d = 0.002\ t^{1.25}$, and assuming a border 30 feet wide and 1,200 feet long, and a depth of application of 4 inches, then

$$4^{1-\frac{1}{1.25}}\ (30)\ (1200)\ (0.002)^{\frac{1}{1.25}} = 720\ Q$$

thus, Q=0.462 c.f.s., or 207 g.p.m.

and t= 440 minutes

In order to achieve the desired objective, one must then adjust the grade of the border, such that the advance and recession curves are parallel. It should be mentioned here that the water need not reach the lower end of the border in 440 minutes but could reach a length shorter than the 1,200 feet and still accomplish the objectives.

One can visualize many objections to such a design. First of all, the resulting grade may not be uniform, nor may it be the most economic grade. Secondly, variations in soil in the border would introduce an extremely complex calculation for the determination of the rates of advance and recession. Thirdly, the method may not work at all because varying the surface grade may not by any means achieve parallel advance and recession curves.

The unit-stream approach, which considers the variables of slope, basic intake rate, and depth of water to apply, is an improvement upon this first method. Although it possesses certain inherent disadvantages, the unit stream is a good method for the design of graded borders and can be used effectively in the absence of other design procedures.

Second Method

The second method, Hall [8/], a modification of the first, sacrifices some efficiency in order to provide more latitude in the manipulation of variables. The basis of the design is the calculation of the rate of advance from the observed or expected infiltration characteristics. The limits of stream size and slope are presumed to be specified on the basis of procedures for minimizing erosion and grading costs. The objectives of this method are similar to the first except that an efficiency of less than 100 percent is realized.

[8/] Hall, Warren A. Design of irrigation border checks. Agr. Engin. 41:439-442. 1960.

The first step in the procedure is to calculate a family of curves for rate of advance, using the known infiltration data. Calculations are made using the most economic slope and probable hydraulic roughness.

The following observations are then made:

The volume of water admitted to the border per unit width is equal to the rate of discharge multiplied by the length of time the water flows into the border. For the preliminary design, this period is also equal to T, the time required for the advance to reach the end of the border, L. The volume of water applied is then

$$V_a = qT \tag{4}$$

The minimum volume of water per unit width required to apply a depth of D feet over the entire length L is

$$V_r = DL \tag{5}$$

The volume admitted to the border must at least equal the volume required. A volume balance can be constructed, however, which expresses the difference between V_a and V_r, presuming that a uniform depth D_o corresponding to an intake opportunity time T is added to the entire field.

$$\text{By definition, } B = qT - D_oL \tag{6}$$

The function B is then constructed for each possible and probable field length. This procedure involves the determination of the time T required for each flow rate to reach a distance L using the advance curves. In most cases, the lengths L will include some maximum length and even fractions thereof. The value of D_o is then determined from the infiltration data, and the corresponding values for B as calculated from equation (6) are plotted as the ordinate against D_o as the abscissa, with length as a parameter, as shown in figure 1. (See footnote 8.)

Only values of B which are greater than zero represent solutions that may possibly apply a depth equal to D_o over the entire length of border. In fact, to allow for nonuniformities and nonparallel advance and recession curves, only values of B greater than some minimum value B_d can be expected to accomplish the objectives. Then, by definition,

$$B_d = fDL \tag{7}$$

where f represents a factor of safety or a measure of the excess water. This function is then also plotted as a series of straight lines on the same graph as B, with B_d as the ordinate and D as the abscissa, as shown in figure 1. The lines shown for the corresponding border lengths are for a constant factor of 0.20.

The intersection of B and B_d for a given length represents the minimum value of B which can be accepted for that length, since lower values presumably would not provide an adequate irrigation to parts of the field. It also

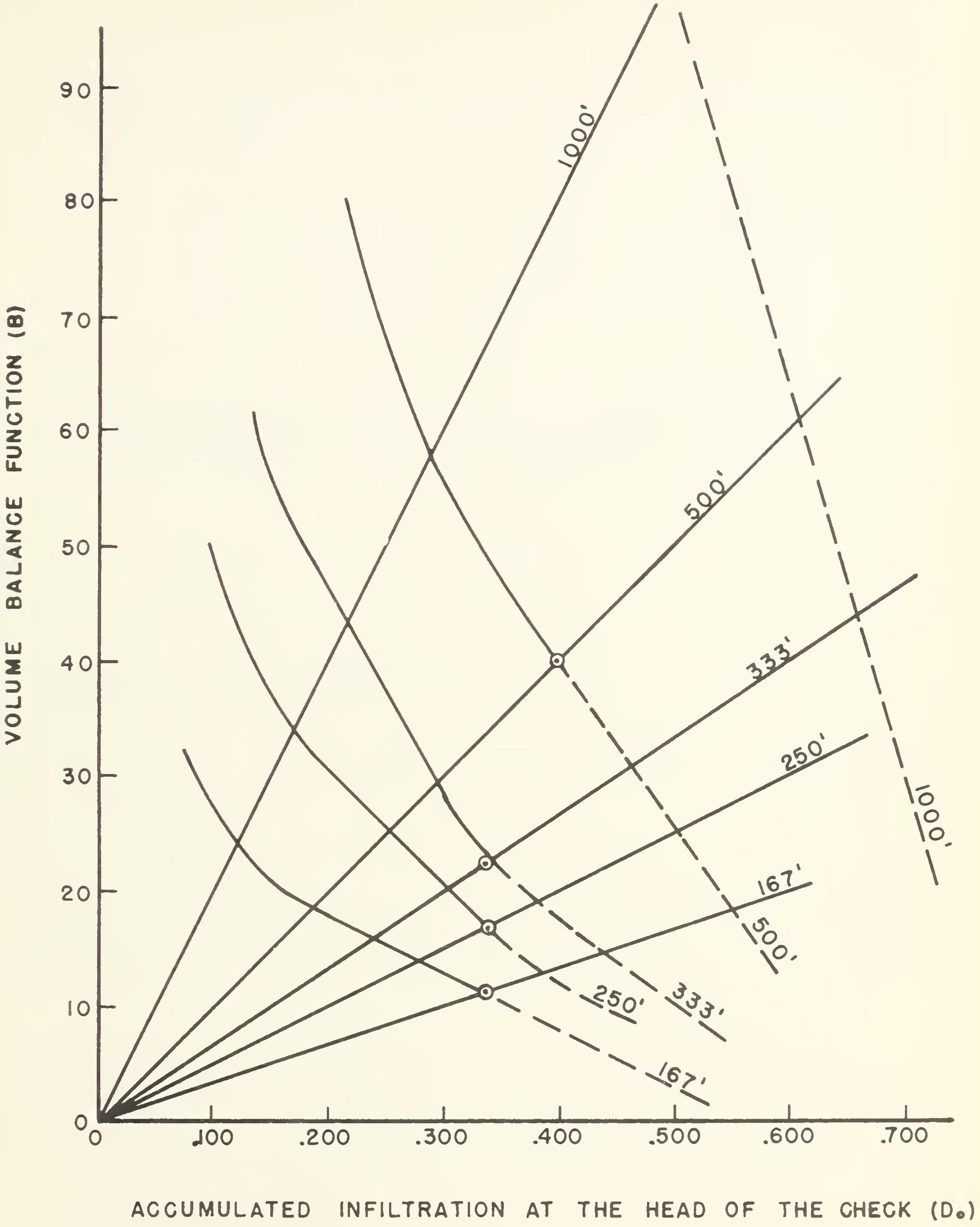

Figure 1.--Volume balance function for selection of desired border length.

represents the point of optimum application efficiency since larger values of B represent a greater than necessary surplus of water admitted to the border. Thus, the intersection of B and B_d nearest to, yet larger than, the design D, will represent the optimum length.

For example, in figure 1, if a depth of application equal to 0.4 foot is desired, the optimum border length is 500 feet. The application efficiency is then equal to

$$E = \frac{DL}{qT}$$

$$\text{or} \qquad E = DL/B+DL \tag{8}$$

In this example, $E = \frac{0.4 \times 500}{40 + 0.4 \times 500} = \frac{200}{240} = 83.3$ percent

The flow rate for this border length is 0.100 c.f.s./ft. unless excessive erosion is expected, and the time T is 40 minutes.

If the solutions obtained by this method result in unsatisfactory efficiency for every economic border length, it may be necessary to modify the design conditions of slope, roughness, or unevenness to get more satisfactory results.

Some comments are in order concerning this method. The factor f was considered to be a constant for lack of better information. In practice, f would be determined from experience as a function of the factors affecting the lack of parallel advance and recession curves. Thus, the method is not precise by any means but depends on experience and empirical observations. Secondly, the length L and time T may be considered as only approximations, for in many cases, more efficient irrigation can be accomplished by turning the water off before it reaches the lower end. This does not invalidate the method, however, but places more dependence on an accurate selection of f.

Third Method

The third method is based upon achieving maximum economic returns from the border system, disregarding irrigation efficiencies as such. The basis of the design is the calculation of monetary returns from a crop grown under various operating conditions and requires some knowledge of the crop yield as a function of water depth applied or soil moisture tension. Data dealing with this relationship are scarce and rather difficult to handle, however.

Presume that rates of advance and recession can be calculated for all conditions of flow rate, grade, roughness, and unevenness, and that infiltration characteristics are known. Then rates of advance and recession are constructed for all the conditions affecting the behavior of the system. This process, although detailed, could be accomplished by proper computer programming.

The numerical time differences between the recession and advance curves can then be determined for intervals of length of the border. With proper infiltration data, the excess or deficient depth of water applied along the length of the border can be calculated. These depths are then translated into crop yield or crop return, and the total effect summed up for the length of the border. From the total returns the water cost and labor cost must be subtracted to permit determination of the net returns of the system. Comparison of net returns for all possible combinations of physical factors then permits the selection of the most economic system.

A limited example of this method illustrates the possibilities for obtaining an economic design.

Given: Data from a border trial at Davis on Yolo silty clay loam. Depth of water to apply to pasture is 2.12 inches, and infiltration is defined by $D = 0.1015\ T^{0.533}$ where D is depth in inches and T is time in minutes. Slope was 0.2 percent and flow rate was 559 g.p.m. into a border 30 feet wide and 1,300 feet long.

Rates of advance and recession were measured for 855 feet and were extrapolated for the remaining presumed length of 1,320 feet. According to the infiltration data, a time of 300 minutes was required to obtain a desired depth of application at the head of the border of 2.12 inches.

Two variables were introduced into the analysis:

length of border (1300, 660, 440 or 330 feet)

time of water flow (300 minutes x 1.0, 0.7, or 0.4)

Thus, 12 separate analyses were made, with T varied from 120 to 300 minutes and L from 330 to 1,320 feet.

For each of the 12 conditions, the time differences between the advance and recession curves were determined, and from the equation for infiltration, the excess or deficiency of water in 100-foot intervals was calculated. Then, assuming that the same conditions existed for each of 19 irrigations, the total excess or deficiency was determined for the season.

A growth function for pasture was hypothesized from some limited, available data. Assuming that 100 percent relative yield has a value of 500 pounds of beef per acre at 28 cents per pound, and that the water cost $3 per acre-foot, the following economic comparison was made.

Table 1.--Comparative Economic Returns of Irrigated Pasture

Length of Border	Value of crop, minus water costs, per acre		
	Fraction of time applied, T_o/T		
	0.4	0.7	1.0
Feet	Dollars	Dollars	Dollars
330	83	119	119
440	89	121	120
660	93	123	120
1,320	75	111	121

If one assumes that other costs are equal, then this simple analysis shows that the 660-foot long border with an operation time of 210 minutes results in the most desirable system. It is also interesting to note that although this combination of factors achieved the maximum economic returns, the most efficient design as far as water use is concerned was the 1,320-foot length and a time equal to 120 minutes. None of the designs is very efficient, however. It is evident that an economic design that would improve the efficiency could be effected and that the example shown here may be an illustration of a rather poor practice.

This last method is not much different from others except that it places a value on the water in terms of crop production. In some cases, this would be quite meaningful, for if a valuable crop is quite sensitive to moisture deficiencies but relatively tolerant to overirrigation, for example, the design could be in the direction of providing adequate irrigation with perhaps some slight overirrigation to insure the proper depth of application. For a low value crop under the same circumstances, the above may not apply and the design may be quite different. The advent of tailwater return systems would also affect the design because this may introduce an entirely different price structure into the design picture. In any case, if the cost or value of water is an accurate measure of the availability of the water resource, this method of design will result in the maximum beneficial use of soil, water, and labor resources. It should provide the best possible design of a border irrigation system.

SUMMARY

The proper design of a border irrigation system is affected by many factors -- some of which are evaluated empirically and others by rational means. In any case, the basis upon which the design is evaluated must be clearly understood, and the objectives and facets of the design adequately outlined. The system must function either to apply a given depth of water as uniformly as physically possible, or to provide maximum net returns as a function of the system design.

This paper illustrates several methods of achieving either objective. It is evident that a knowledge of the behavior of the system is paramount, however; without this knowledge, design methods are inadequate and may not achieve either objective. Research and field trials to evaluate the results of research must be stimulated and properly guided, especially as agriculture is forced to the poorer soils and water becomes more valuable and, in many instances, limited to a large degree. It is the author's hope that in the near future the understanding of the behavior of an irrigation system may have progressed to the point where the rancher or farmer can be assured of the maximum economic returns and at the same time make the best use of a valuable natural resource.

FURROW IRRIGATION

DESIGN PROCEDURES AND RESEARCH NEEDS FOR THE FURROW METHOD OF IRRIGATION [1]

by

J. T. Phelan [2]

RESEARCH NEED

In the July 1, 1959, report from the Soil Conservation Service to the Agricultural Research Service, two research needs of major importance to the design of the furrow method of irrigation were listed. Excerpts from this publication are:

> "II WATER MANAGEMENT
>
> A. Irrigation
>
> 4. Hydraulic characteristics of surface methods of irrigation.
>
> Empirical methods now commonly used in the design of surface irrigation systems are inadequate. Present methods should be revised or new procedures developed. - - -
>
> 10. Limitation on design of surface irrigation systems due to rainfall that creates erosion and surface drainage problems.
>
> Irrigation introduces additional erosion and drainage hazards in humid areas. The modifications that must be made - - - to properly control erosion from rainfall and provide adequate drainage should be studied and more clearly defined."

The objective of this paper is to expand on the needs by showing: (a) The procedures presently in use by the SCS in designing furrow irrigation; and (b) the apparent weakness in the design procedures.

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[1] Contribution from Soil Conservation Service, U. S. Department of Agriculture.

[2] Irrigation Engineer, Engineering and Watershed Planning Unit, Soil Conservation Service, U. S. Department of Agriculture, Lincoln, Nebr.

DESIGN

Nomenclature

F_n = Net irrigation application in inches

F_g = Gross irrigation application in inches

E = Design efficiency in percent

I_b = Basic intake rate of soil under flooding conditions in inches/hour used to identify a design intake curve.

I_f = Average furrow intake rate for a field application of F_n inches in g.p.m./100 ft.

S = Slope of furrow in percent

s = Slope of furrow in feet per foot

L = Length of run in feet

L_m = Maximum length of run in feet

w = Furrow spacing in inches

Q_i = Initial furrow stream in g.p.m.

Q_e = Maximum nonerosive furrow stream in g.p.m.

Q_c = Maximum capacity of furrow in g.p.m.

T = Time of irrigation in hours

t = Time for net irrigation application, F_n, to be absorbed in minutes

n = Coefficient of roughness in Manning's formula

F_n - Net Irrigation Application

For purposes of this paper, this value is considered as given. It is derived from a knowledge of the depth and pattern of moisture extraction by the crop (Research Need II-A-2) and the amount of moisture that is required to fill the root zone to this depth (Research Need II-A-6).

E - Design Efficiency

The design efficiency is also given. The values presently in use are based on multiple judgment of SCS specialists who have been making irrigation evaluations and scattered information gleaned from ARS and college research reports. More information is needed as to the effect of slope, intake characteristics, and depth of application on the efficiency that can be expected from the various methods of irrigation.

F_g - Gross Irrigation Application

$$F_g = \frac{100\ F_n}{E}$$

I_b - Basic Intake Rate of Soil under Flooding Conditions

For design purposes, some method is necessary to characterize the soil. Commonly, soil is identified by texture but since the advance-time relationship is dependent on the intake characteristic, it appears best to group soils into intake families. At the present time, in the northern Plains we are using eight families to embrace all soils from the lowest to the highest intake. Cylinder infiltrometer tests run on irrigated alfalfa fields 2 to 5 years old provide the basis for comparison between soils. Typical intake-time curves have been developed for each of the eight and each curve is given a name corresponding to its basic intake rate. In the southern Plains two additional curves are used for soils having clays with high shrink-swell characteristics. The intake family into which the soil falls must be known for design purposes.

S - Slope of Furrow

The slope of the furrow is an important element in design. Other site conditions being equal, the slope will determine which of three following groupings will govern the design approach.

(a) Normal furrows. The design is based upon the relationship between the time for the water to advance across the field and the total irrigating time. Here the water in temporary storage above the ground surface drains away very rapidly after the stream is turned off and the time of recession is unimportant. Slopes are usually about 0.5 percent or above.

(b) Flat furrows. These have low gradients and the recession time becomes an important feature in design.

(c) Level furrows. Here the water is applied at some minimum rate to induce ponding over the field.

Q_c - Maximum Capacity at the Furrow

For a given slope, a furrow has a flow capacity limited by its physical size. Irrespective of other limitations, the safe capacity of the furrow must be known since on flat slopes it may limit the introduced stream size.

The size of the furrow is dependent upon the cultural practices followed and may be limited by the furrow spacing. It appears that in a great many instances the furrow shape can be considered parabolic, and the depth of the furrow is a function of the furrow spacing (w). Limited observations made by field personnel seem to indicate that most furrows in an area, whether they be deep furrows on a wide spacing or shallow furrows with a narrow spacing, seem to develop about the same hydraulic radius for a given depth.

While a computation can be made to determine the maximum furrow capacity using Manning's formula, in practice it is normal to establish the value Q_c for each crop by observation. For example, in one area the maximum capacity of potato, sorghum, and corn furrows may be considered to be 50 g.p.m., while sugar beet and bean furrows may be only 20 g.p.m. An empirical rule used in the Southwest is Q_c equals 75 times the furrow cross-sectional area in square feet. Because of the great variability of the cultural practices and the resulting difference in furrow cross section from irrigation to irrigation and from farm to farm, it is doubtful if more precision is warranted.

Q_e - Maximum Nonerosive Furrow Stream

In the late 40's, Criddle developed a procedure for determining the proper length of runs, sizes of furrow streams, and spacing of furrows on irrigated lands. This procedure required a field test on each field and over the years a great many evaluations were run by SCS and college personnel. In each evaluation, those running the test observed different size streams and arrived at a personal estimate. There were often wide differences of opinion among observers as to when a stream could be considered erosive. Criddle, at that time, acted as a central gathering point for all evaluations and his analysis indicated that the maximum nonerosive stream could be expressed empirically as

$$Q_e = \frac{10}{S}$$

This relationship, though very simple, does closely approximate a constant velocity in a parabolic furrow as computed by Manning's formula. Since it is a limit only, it appears to be satisfactory for design purposes.

Q_i - Initial Furrow Stream

The initial furrow stream is the largest stream used in furrow irrigation and, therefore, must not exceed either Q_c or Q_e.

L_m - Maximum Length of Run

In the evaluations mentioned above, which were collected by Criddle, the maximum length of run was determined. The criteria used to establish this maximum length was the distance that the maximum allowable furrow stream, Q_i, would advance within one-fifth of the time required to complete the application F_n to all points in the field.

Much of the data gathered by field personnel had the following limitation:

(a) The technique of determining the time required to complete the application F_n was still relatively crude.
(b) It was assumed that the recession time in the furrow was negligible. This is true only for furrows with an appreciable slope.

However, the procedure was a significant step forward since it did provide a rational basis for designing the proper length of run.

Criddle analyzed the reported maximum length of run as influenced by slope S, and depth of application F_n. He proposed the following:

$$L_m = \frac{K F_n^{0.5}}{S^{0.555}}$$

K = Factor based on soil texture

This relationship was later modified in the northern Plains by relating the factor K to intake rate instead of texture.

$$\text{Log } K = 1.52 - 0.2\ I_b$$

Also, since Criddle's relationship assumed the use of the maximum non-erosive stream, the value $S = \frac{10}{Q}$ was substituted giving

$$L_m = \frac{K F_n^{0.5}\ Q_i^{0.555}}{3.58}$$

Tables for each of the eight intake curves were developed for use by field personnel. The above procedure seems to give reasonable answers on slopes above 0.5 percent. It appears to be conservative for slopes below that value. It apparently falls down when the stream size is smaller than Q_e. For instance, a stream of 3 g.p.m. has the same length of run if the slope was 0.2 percent or if it was 3 percent. Certainly there must be a difference in the advance-time relationship.

In the southern Plains, the usual irrigation slope is quite flat and Criddle's empirical formulas have not found much acceptance. There, the recession of a furrow stream is of great import and furrows have many of the characteristics of borders. To fill the need, the following empirical formulas were developed by Lester Lawhon of the Engineering and Watershed Planning Unit, Fort Worth, Tex. They are based upon the furrow cross sections commonly used in the area.

For very flat slopes:

$$Q_i = \frac{I_f L}{100} + \left[\frac{L}{5.65 \ \frac{t}{4} \left(\frac{1.486}{n} \right)^{0.75} s^{0.375}} \right]^{4.0}$$

I_f = Furrow intake in g.p.m./100 ft. at time 1/4 t.

For level furrows:

$$Q_i = \frac{6 \ F_n \ L}{t}$$

They work satisfactorily for the range of conditions for which they were developed.

I_f - Average Furrow Intake for a Field Application of F_n

The intake characteristics of furrows are different from those prevailing under flooding methods of irrigation. Techniques have been established for measuring furrow intake, but little data are available to associate the many variables that affect intake so that a definite design value can be determined for a given site condition. Some of the factors that may affect average intake in furrows directly or indirectly are:

(a) Soil type
(b) Size of stream - Q
(c) Slope of furrow - s
(d) Roughness coefficient - n
(e) Furrow cross section
(f) Furrow spacing - w
(g) Total depth of application - F_n

We have no standard method for estimating values of I_f. In the Far Western States, a design value is selected from a range of values tabulated according to surface texture and slope.

In the southern Plains, a relationship between the percent of the field covered and the ratio between field intake and cylinder intake was developed. This tentative relationship is shown in figure 1.

In the northern Plains, a relationship for furrow intake with basic cylinder rate, stream size, slope and net application was developed. This is based on the following:

$$I_f = C_s \ C_d \ I_o$$

where

$$I_o = \text{Antilog} \left[0.0051 \ I_b^{-0.29} \ Q_i + \log 2.54 \ I_b^{0.42} \right]$$

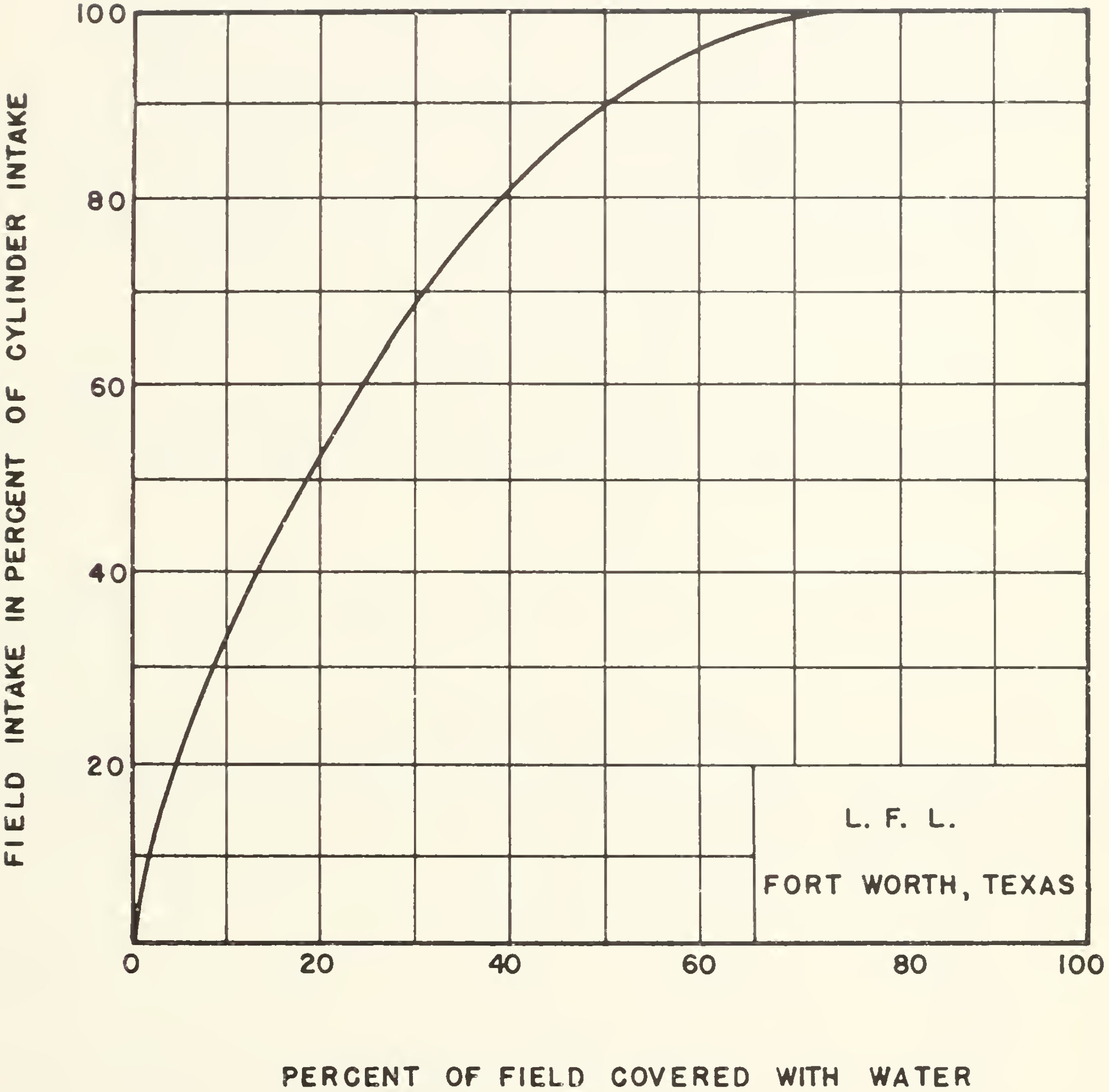

Figure 1.--Tentative relation of cylinder intake to field intake with furrows.

I_o = Average furrow intake for an application of 1 inch on a slope of 1 percent.

$C_s = S^{-0.22}$

$C_d = \frac{F_n t_1}{t}$

t = time required for an application of F_n with cylinders.

t_1 = time required for an application of 1 inch with cylinders.

None of these three procedures is completely satisfactory. They were developed by SCS personnel to provide a basis for estimating in a situation where the basic relationships are not known. It is necessary for field personnel to make an estimate for a specific site condition without a long series of investigations. SCS engineers are presently examining present procedures to see if a uniform tentative procedure applicable to all areas can be developed prior to the completion of needed research.

T - Time of Irrigation

The time of irrigation may be computed from the net depth of application, furrow spacing, and average furrow intake rate. In the northern Plains and west coast areas where slopes are appreciable, the following is used:

$$T = 0.108 \frac{d \quad w}{I_f}$$

This allows for a length of run that will have a time of advance equal to one-fifth T.

In the southern Plains where slopes are flat, the recession of the furrow stream is considered equal to the time of advance. The time of irrigation is computed in a manner similar to borders; that is, the time required to apply the gross application to the area represented by the furrow length L times the spacing w/12, with the stream Q_i.

$$T = \frac{0.0866 \; L \; w \; F_n}{Q_i \; E}$$

w - Furrow Spacing

When furrows are used with row crops, the dimension w is determined by agronomic requirements. With close-grown crops, small furrows, commonly called corrugations, can be spaced in accordance with the irrigation requirement. The most desirable spacing is such that the lateral movement of the soil moisture will nearly "black out" the ridges by the time the irrigation is complete.

From observational studies made by the SCS in the northern Plains in 1955, the following spacings were recommended. Spacing increases with depth of application and as the soil texture becomes finer.

Table 1.--Recommended Corrugation Spacings

Net depth of irrigation	Soil Texture			
	Heavy H	Mod. Heavy F	Medium M	Mod. Light S
Inches	Inches	Inches	Inches	Inches
2	18	18	15	15
3	20	20	18	15
4	22	22	20	18
5	24	24	22	20
6	24	24	24	22

In the southern Plains, the following rule of thumb has been used:

$$w = (2F_n + 6) W_c$$

where W_c = water-holding capacity of soil in inches per foot. A more refined procedure which considers additional factors is needed.

LIMITATIONS DUE TO RAINFALL

A system of furrow irrigation can be properly designed to adequately apply irrigation water and still be unsatisfactory when placed in the wrong environment. This has caused some of the so-called differences in irrigation design between the "humid" and "arid" parts of the United States.

A properly designed irrigated field must simultaneously satisfy criteria for each of the following:

(a) Efficient application of irrigation water.
(b) Protection from erosion caused by rainfall.
(c) Drainage to eliminate wetness.

Criteria for (b) and (c) are greatly influenced by climate and will vary widely from "arid" to "humid" areas.

Maximum Allowable Slope

An irrigation furrow usually has a continuous slope to allow the application of irrigation water. The size of the irrigation stream is subject to control and may be maintained at a point where it is nonerosive. However, erosion may still occur from the runoff produced by heavy rains. This flow is dependent upon site conditions and is not subject to management control. To prevent damage from heavy rains, the slope must be limited or the length of run reduced, or both, to provide for disposal of this runoff water at nonerosive velocities.

The mechanics of erosion from rainfall on cultivated fields are not well understood. Most of the studies on this problem have been made east of the Missouri River and have been made on slopes greater than those generally prevailing in most irrigated areas.

In the northern Plains, this problem is very important since there is pressure to irrigate steep slopes in areas where intense storms are common. The SCS has taken two approaches to the solution of this problem. The first is based on the so-called Musgrave formula which expresses sheet erosion as a function of (a) Soil Factor, (b) Cropping Factor, (c) Slope, (d) Length of slope, and (e) 30-minute precipitation on a 2-year frequency.

Assuming values for the factors and reducing, in the northern Plains we have used the following for a guide:

$$S_{Max.} = P_{30}^{-1.3}$$

where $S_{Max.}$ = Maximum permissible furrow slope in percent.

P_{30} = 30-minute rainfall on 2-year frequency

Another approach is based on the maximum allowable velocity in a furrow. Through hydrologic procedures, the rate of runoff can be determined and with knowledge of the furrow size and slope, a velocity can be computed. This velocity must be nonerosive. The difficulty with the latter approach is that we do not know the allowable velocity under conditions of storm runoff nor do we know the hydraulic characteristics of these small flows.

Minimum Allowable Slope

In some areas seasonal wetness interferes with cultural practices and crop production. In these sites, a certain minimum furrow grade is required to provide adequate surface drainage. So far, our designs are based upon local opinion and experiences.

CONCLUSION

The above discussion presents current procedures with the knowledge that some of them are inadequate. It must be recognized that the SCS is called upon to make technical recommendations for a great variety of site conditions. Research data that presents an answer for one soil, slope, or climatic condition are only part of the answer. It is obvious that research cannot be done on all soils, all slopes, or all climatic conditions and so the research need is not fully met until the basic relationship between the various factors is solved.

FURROW HYDRAULICS STUDY AT THE SOUTHWESTERN IRRIGATION FIELD STATION [1]

by

Hollis Shull [2]

INTRODUCTION

This report describes the furrow hydraulics study being conducted at the Southwestern Irrigation Field Station at Brawley, Calif. The purpose of this study is to develop a method by which the rate of advance of irrigation water in furrows can be predicted prior to irrigation. Prediction of the rate of advance of irrigation water in furrows is necessary for the proper design of new furrow irrigation systems and for the proper operation of existing systems. Future developments, such as automatic gravity irrigation systems, will increase the need for a method to predict the rate of advance of irrigation water in furrows. This report presents the field procedures followed and the measurements obtained, infiltration in irrigated furrows, and a rational approach to the development of a rate of advance equation with some of the problems encountered in developing an equation by this method.

FIELD PROCEDURES FOLLOWED

Three adjacent furrows were irrigated during each field trial. All measuring equipment and instruments were placed in the center furrow. The rate of inflow was the same in all three furrows and was constant during any one field trial. The rate of inflow was varied for different field trials and ranged from 6 to 30 g.p.m. during the trials that have been completed to date.

The following measurements were made during the field trials:

(a) Inflow to furrows was measured and controlled by calibrated orifice box containing three identical sharp-edge circular orifices spaced on 40-inch centers. The orifice flow measurements were supplemented by measurements with a Sparling meter in the supply line to the orifice box, and a calibrated trapezoidal flume in the center furrow. The fact that there was never complete agreement between flow measurements by the three different methods emphasized the difficulty of obtaining accurate measurement of the inflow to furrows under field conditions. Differences of 10 percent in the measurement of inflow by the three methods were common.

(b) Distance of advance of water in the furrow as a function of time.

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[1] Contribution from Soil and Water Conservation Research Division, Agricultural Research Service, U. S. Department of Agriculture, California Agricultural Experiment Station, cooperating.

[2] Agricultural Engineer, Western Soil and Water Management Research Branch, Soil and Water Conservation Research Division, Agricultural Research Service, U. S. Department of Agriculture, Brawley, Calif.

(c) Slope of the furrow bottom before irrigation.

(d) Slope of the water surface in the furrow was determined during irrigation. Relative water surface elevations at seven different locations in the furrow were obtained with a furrow manometer. A staff gage placed in the furrow at one of the manometer hose locations related the water surface readings to the furrow profile so water depth in the furrow at each manometer tube location could be determined.

(e) Furrow cross sections before irrigation were obtained by photographing the end plates on both the blocking and bypass furrow infiltrometers.

(f) Water temperature in the furrow.

(g) Infiltration measurements in the furrow were made prior to irrigation with a blocking furrow infiltrometer and during irrigation with a bypass furrow infiltrometer. Although it was recognized that infiltration measurements exhibit considerable variation over small areas of seemingly uniform soils, equipment and labor considerations limited infiltration measurements in the Brawley study to one measurement with each infiltrometer for each field trial.

INFILTRATION IN IRRIGATED FURROWS

Infiltration is a field variable that is difficult or impossible to control and difficult to measure accurately. A bypass furrow infiltrometer, which measures infiltration during irrigation, was developed as a part of the Brawley furrow hydraulics study [3/]. The bypass furrow infiltrometer simulates the conditions that occur in an irrigated furrow as closely as is possible within an infiltrometer enclosure. The accuracy with which the instrument estimates actual furrow infiltration may be limited under some conditions because only a small segment of furrow is isolated and water is not flowing in the infiltrometer enclosure.

Infiltration as measured with the bypass furrow infiltrometer can be expressed by an equation of the form, $I = C + A\sqrt{T} + BT$, where:

I = the total infiltration, after water has been on a location in the furrow for time, T, minutes. The units of I used in the Brawley study are cubic feet per foot length of furrow.

C, A, and B = constants

It is probable that a more general furrow infiltration equation would also include water depth in the furrow as a variable.

[3/] Shull, Hollis, A Bypass Furrow Infiltrometer. Presented at the 1959 winter meeting, ASAE, submitted for publication in Agricultural Engineering.

To be useful in an equation, to predict the rate of advance of irrigation water down furrows, infiltration must be measured prior to irrigation. The blocking furrow infiltrometer is a logical instrument to measure infiltration in furrows prior to irrigation [4]. In addition to the period of time water has been applied, infiltration in a furrow during irrigation is a function of the rate of increase of depth of water in the furrow. Since the water level in the blocking infiltrometer is constant during infiltration measurement, the infiltrometer cannot be expected to provide a measurement that will be the same as experienced in a furrow during irrigation. However, if the rate at which the depth of water in the furrow increases during irrigation is known, it should be possible to utilize the furrow blocking infiltrometer data to develop an infiltration equation that will predict furrow infiltration during irrigation. Attempts to use blocking furrow infiltrometer data at Brawley have not been successful to date when compared with infiltration measured during irrigation with the bypass furrow infiltrometer.

The rate at which the depth of water in a furrow increases during irrigation varies continuously from one end of the furrow to the other. Because of this variation, furrow infiltration characteristics will change continuously throughout the irrigated furrow. This variation could be considered in a rate of advance equation. However, the development of such an equation would be much more complex than if infiltration were assumed uniform at all locations in the furrow at a given time after water reaches each location.

Furrow shape, slope, and roughness influence the depth of water in an irrigated furrow. Therefore, since infiltration is affected by water depth in the furrow, furrow infiltration will be a function of furrow shape, slope, and roughness, as well as a function of time. A more complete understanding of furrow infiltration will be needed before a satisfactory rate of advance equation for furrows can be developed.

THE RATIONAL APPROACH TO THE FURROW STUDY

The following equation should be true for any irrigated furrow:

$$Q\,T = I_t + V_t$$

where: Q = inflow rate to the furrow, cubic feet per minute.

T = elapsed time, minutes, since irrigation started.

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[4] James A. Bondurant, Developing a Furrow Infiltrometer. Agr. Engin. 38(8): 602-604, August 1957.

I_t = total infiltration volume, cubic feet, in the total wetted portion of the furrow in time, T, minutes. (Evapotranspiration losses are assumed to be negligible.)

V_t = total volume of water, cubic feet, in storage in the furrow at time, T, minutes.

Analysis indicates that in order to solve for I_t and V_t in the above equation, the rate of advance of water in the furrow must be known. Therefore, a rate of advance can be arrived at only by trial and error.

A solution to some form of the equation $Q\ T = I_t + V_t$ has been developed by a number of investigators -- O. W. Israelsen [5], W. A. Hall [6], and M. R. Lewis and W. E. Milne [7]. Several simplifying assumptions were made in all of the solutions and none of the methods developed is in common use in irrigation system design.

The rational approach to the furrow hydraulic problem investigated at Brawley is based on the following equations and assumptions:

$$I = C + A\sqrt{T} + B\ T \qquad (1)$$

where: I = total infiltration, cubic feet per foot length of furrow in elapsed time, T, minutes.

T = total time in minutes water has been at the location in the furrow where the value of I is desired.

C, A, and B = constants.

$$X = F\ T^G \qquad (2)$$

where: X = the distance, feet, that water has advanced down the furrow in time, T, minutes.

T = the elapsed time since irrigation started, minutes.

F and G = constants.

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[5] O. W. Israelsen, Irrigation Principles and Practices. Second Ed., John Wiley and Sons, 123 pp., 1950.

[6] Warren A. Hall, Estimating Irrigation Border Flow. Agr. Engin. 37: 263-265, April 1956.

[7] M. R. Lewis and W. E. Milne, Analysis of Border Irrigation. Agr. Engin. 19:267-272, June 1938.

$$d = R\, s'^{u} \tag{3}$$

where: d = the vertical distance, feet, from the water surface in the furrow to a horizontal line intercepting the average furrow slope at the location of the wetted front, at a distance s' feet upstream from the wetted front.

R and u = constants. (See figure 1.)

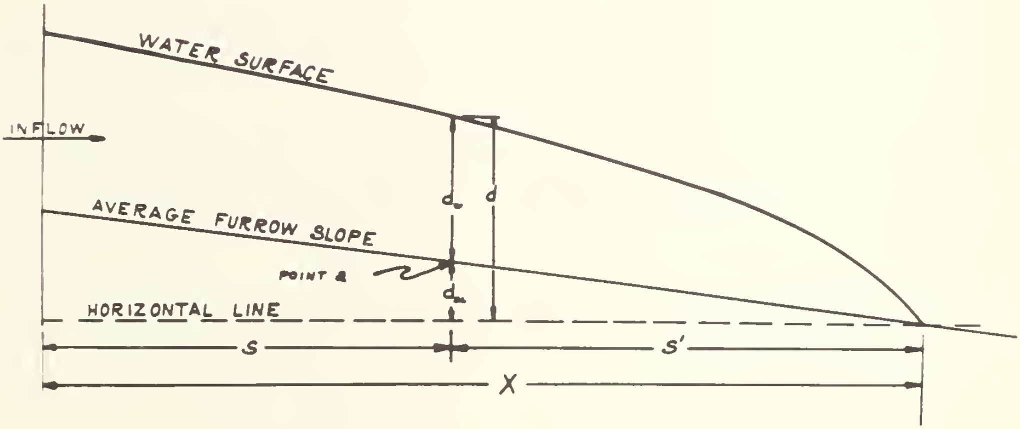

Figure 1.--Diagram showing designation of factors used in the rate of advance analysis.

$$d_{s1} = \frac{S\ s'}{100} \tag{4}$$

where: d_{s1} = the vertical distance, feet, from the furrow bottom to the horizontal line extending from the wetted front - average furrow slope intercept, at a distance s' feet upstream from the wetted front.

S = the average slope of the furrow, percent. (See figure 1.)

$$d_w = d - d_{s1} \tag{5}$$

where: d_w = the depth of water, feet, in the furrow at a location s' feet upstream from the wetted front. (See figure 1.)

$$A = M\, d_w^{\,n} \tag{6}$$

where: A = the cross-section area, square feet, of the water in the furrow when the water depth in the furrow is d_w feet.

M and n = constants.

The total volume of infiltration in the entire wetted length of the furrow, I_t, at any time, is a function of the time water has been on every point in the furrow. The time water has been on any one location in the furrow, T_a, is the time since irrigation started minus the time required for water to have advanced to that location. In figure 1, for example, the time water has been on point, a, is the time required for water to have advanced X feet minus the time for water to have advanced s feet. The equation for T_a is:

$$T_a = T_X - T_s \qquad (7)$$

where: T_a = the time water has been on point a in the furrow, minutes.

T_X = the time required for water to have advanced X distance, or the total time water has been in the furrow, minutes.

T_s = the time required for water to have advanced s distance, minutes.

The total infiltration at location a, at any time, T_a, can be expressed as follows:

$$I_a = C + A\sqrt{T_a} + B\,T_a \qquad (1a)$$

Substituting (7) in (1a):

$$I_a = C + A\sqrt{T_X - T_s} + B\,(T_X - T_s) \qquad (1b)$$

The total infiltration volume in the entire wetted length of the furrow is the sum of the total infiltration at every point in the furrow and may be expressed as follows: (See figure 1.)

$$I_t = \int_o^X I_a \; ds \qquad (8)$$

Substituting (1b) in (8): (8a)

$$I_t = \int_o^X \left(C + A\sqrt{T_X - T_s} + B\,(T_X - T_s)\right) ds$$

From equation (2):

$$T_X = \left(\frac{X}{F}\right)^{\frac{1}{G}}, \quad \text{AND} \quad T_s = \left(\frac{s}{F}\right)^{\frac{1}{G}} \qquad (2a)\ \&\ (2b)$$

Substituting (2a) and (2b) in (8a):

$$I_t = \int_o^X \left(C + A\left(\left(\frac{X}{F}\right)^{\frac{1}{G}} - \left(\frac{s}{F}\right)^{\frac{1}{G}}\right)^{\frac{1}{2}} + B\left(\left(\frac{X}{F}\right)^{\frac{1}{G}} - \left(\frac{s}{F}\right)^{\frac{1}{G}}\right)\right) ds \qquad (8b)$$

The following is a solution to the above equation for I_t:

$$I_t = X \left(C + A\sqrt{T}\,(K) + \frac{B\ T}{G + 1}\right) \qquad (9)$$

$$\text{where:} \quad K = 1 - \frac{G}{2(G + 1)} - \frac{G}{8(G + 2)} - \frac{G}{16(G + 3)}$$

(the expression for K omits all but four terms of a binomial expansion.)

The above equation shows that calculation of the total volume of infiltration in the entire wetted length of a furrow at any time is dependent upon the rate at which irrigation water advances down the furrow, as well as the infiltration characteristics of the furrow.

An equation for the total volume of water in storage in a furrow at any time can be derived by a similar procedure. The total volume of water in storage in a furrow after water has advanced down the furrow a distance X can be expressed as follows: (See figure 1.)

$$V_t = \int_o^X A_a\, ds' \qquad (10)$$

Substituting (3) and (4) in (5), and substituting (5a) in (6):

$$d_w = R\ s'^u - \frac{S\ s'}{100} \qquad (5a)$$

$$A = M\left[R\ s'^u - \frac{S\ s'}{100}\right]^n \qquad (6a)$$

Substituting (6a) in (10)

$$V_t = M\int_o^X \left[R\ s'^u - \frac{S\ s'}{100}\right]^n ds' \qquad (10a)$$

A solution to (10a) is:

$$V_t = M\,R^n \left[\frac{X^{un+1}}{un+1} - \frac{n\ S\ X^{2+un-u}}{100(2+un-u)R} + \frac{n(n-1)\ S^2\ X^{3+un-2u}}{20{,}000(3+un-2u)R^2}\right] \qquad (11)$$

The above solution omits all but three terms of a binomial expansion.

The above equation shows that calculation of the total volume of water in storage in a furrow at any time is also dependent upon the rate at which irrigation water advances down the furrow, as well as the depth of water in the furrow and the furrow shape. The effect of roughness in the furrow has been omitted because no data are available which would permit its use in the analysis. Roughness probably would influence the values of R and U in the calculation of V_t and, as mentioned previously, roughness would probably influence infiltration also.

Since solution of the rational equation, $Q\ T = I_t + V_t$, requires knowledge of rate of advance, X, this equation can be solved for X by trial and error if either F or G, from the rate of advance equation, can be determined. F is the distance, in feet, that water will progress down the furrow during the first minute of irrigation. If an equation can be developed to estimate F closely, and values for X and T assumed, the value for G can be estimated as follows:

$$G = \frac{\log X - \log F}{\log T} \tag{12}$$

The estimated solution for G, and the assumed values of X and T can be substituted in the equations for I_t and V_t. Then by trial and error values of T and X can be found so that $I_t + V_t = Q\ T$. Using these values of X and T, the rate of advance equation, $X = F\ T^G$, can be written with a greater accuracy. If the constants in the equations for I, d_w, A, and the value for F, are correct, the rate of advance equation should be reasonably accurate.

The following equation to estimate F was developed from data from the Brawley study:

$$F = 3.52\ M^{0.49}\ Q^{0.35}.$$

where Q = inflow to the furrow, g.p.m.

M = the value for M from the equation, $A = M\ d_w^{\ n}$

SUMMARY

The foregoing discussion indicates that a procedure for predicting the rate of advance of irrigation water down furrows can be developed. At the present time, however, it is not possible to accurately predict either the infiltration characteristics of irrigated furrows or the water surface profile. The infiltration characteristics are needed to calculate the total volume of infiltration. The water surface profile is needed to calculate the total volume of water stored above the soil surface in the furrow. Further studies of both furrow infiltration and water surface profile are necessary before a workable, accurate rate of advance equation for irrigated furrows can be developed.

SUMMARY OF HYDRAULICS OF FURROW IRRIGATION STUDIES IN MISSOURI [1]

by

John F. Thornton [2]

The design of surface irrigation systems involves flow phenomena that are extremely complex. The complexity of these flow phenomena has been widely recognized, but in most cases it has been underestimated. The differences between calculated and observed flow processes, such as rate of advance, have frequently been attributed to insufficient information relative to intake rates. However, in reviewing the literature it appears that more work has been done on intake rates than has been done on the hydraulics of surface irrigation.

Studies to determine the effects of rate of water application, intake rate, slope, shape, and roughness on the advance rates under furrow irrigation were started in 1957 in Missouri. The initial phases of the study were conducted on Sharon silt loam at Elsberry, Mo.

Precisely graded plots with 0.25-percent slope were established to evaluate the effects of roughness and channel shape. Two shapes of furrows were studied. One was a flatbottom furrow, 20 inches wide, made with a special sweep attached to the rear of the tractor cultivator. The sweeps on the front were of the conventional type. The other furrow shape studied was made using only conventional cultivator sweeps in front and back. The plots were 20 feet wide and 800 feet long, and the crop grown was corn with a row spacing of 40 inches.

Meters and gated pipe constituted the inflow regulating devices, and a flume with an automatic time-recording device measured outflow at the end of the furrow.

The rate-of-advance curves indicate that the furrow shape will affect the rate of advance of the water in the furrow. It took 4 hours for water to travel 800 feet in the conventional furrow as compared to 3 hours in the flatbottom furrow. The difference in rate of advance between the two types of furrows was due to the effect of the 20-inch sweep in moving most of the dry, loose soil from the furrow. The dry, loose soil remaining in the conventional shape furrow resulted in a higher initial intake rate. The 20-inch sweep also probably pressure-sealed a larger part of the furrow than the smaller sweeps did. On log-log paper, the rate-of-advance data vs. time plotted as a straight line. Theoretically, this should be true only with uniform flow.

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[1] Contribution from Soil and Water Conservation Research Division, Agricultural Research Service, U. S. Department of Agriculture, and Missouri Agricultural Experiment Station, cooperating. Approved by Experiment Station Director as Journal Series No. 2114.

[2] Agricultural Engineer, Eastern Soil and Water Management Branch, Agricultural Research Service, U. S. Department of Agriculture, Columbia, Mo.

The equations derived for rate of advance were as follows:

Conventional shape:

$$y = 57.5\ X^{0.478}$$

Flatbottom shape:

$$y = 63.1\ X^{0.490}$$

where y = distance in feet and X = time in minutes.

The field-intake rate averaged 0.27 inch per hour for the first 420 minutes. After 420 minutes, the field-intake rate was 0.135 inch per hour. The intake rate varied directly with stream width.

Intake rate increases with temperature because of the decrease in the viscosity of water. Inasmuch as the flow into the soil is usually approximately laminar, at least for compact, finely textured soils, the rate of intake should vary inversely as the kinematic viscosity. On this basis, an increase in water temperature of 50° F. should approximately double the intake rate. Experimental verification of this conclusion is, however, lacking at present. The temperature of the water increased uniformly from 56° at inflow to 75° at outflow. The air temperature was 85° to 90° during the study (July and August). At this time the corn provided a good shade for the furrow. The 19° difference in temperature over the length of the furrow should increase the average intake rate of the furrow about 20 percent.

When the logarithm of the intake rate was plotted against the logarithm of time, the resulting curve was essentially a straight line. The straight line on log-log paper fits the equation

$$i = at^b$$

where,

i = intake rate at time t

and

a and b are constants.

Because these curves fit this general equation, it was possible to subject each of the plot-irrigations to a linear regression analysis by the least squares method. When both sides of the intake equation are expressed as logarithms, the resulting equation becomes $\log i = \log a + b \log t$, which is similar to the general linear equation of a straight line $y = c + mx$. The equation for intake rate was as follows:

$$i = 0.316\ t^{-0.5}$$

where,

i = intake rate in inches per hour

and

t = time in minutes.

The transition between laminar and turbulent flow takes place in a range of R values (Reynolds numbers) varying from 600 to 1,200. Dimensionally, the Reynolds number is proportional to the ratio of the inertia forces of an element of fluid to the viscous force acting on the fluid. Reynolds number was determined by using the formula $R = \frac{Vy}{\nu}$, where "V" is the mean velocity, "y" is the normal depth of flow and "ν" is the kinematic viscosity. The average Reynolds number was 2,050 for both furrow shapes which indicated turbulent flow. A Reynolds number of this magnitude should have very little effect on intake rates or the coefficient of roughness. Intake rate and coefficient of roughness would both be affected if erosion took place, but there was no erosion in the furrow.

The influence of furrow shape and stream size on the roughness coefficient was determined by Manning's formula

$$V = \frac{1.486 . R^{2/3} S^{1/2}}{n}$$

where

V = mean velocity of water

$R = a/p$ = hydraulic radius

S is the slope of energy line

n is the coefficient of roughness

The data on coefficient of roughness are shown in table 1. The "n" value was determined after running water down the furrow for 5 hours, at which time the intake rate was constant at 0.20 inch per hour for both furrow shapes.

TABLE 1.--Characteristics of the stream flow in furrows

Furrow shape	Flow	Depth	Mean velocity	Froude number	Manning's
	c.f.s.	Feet	Ft./sec.	$F = \sqrt{\,}/\sqrt{gd}$	"n"
S_1[1]	0.053	0.15	0.663	0.30	0.021
S_1	.024	.10	.448	.25	.029
S_1	.013	.05	.304	.24	.035
S_2[2]	.024	.15	.421	.19	.026
S_2	.013	.10	.335	.19	.029

The value of "n" varied from 0.021 for a stream size of 0.053 c.f.s. to 0.035 for a stream size of 0.013 c.f.s. in the flatbottom furrow. The size of the furrow stream affects both the mean velocity and "n". The larger the stream size, the higher the velocity and the lower the "n" value.

The shape of the furrow affected the value of "n" to a lesser degree than did stream size.

The Froude flow criterion varied widely depending upon the location of the depth measurement. It was, however, very difficult to measure depths and velocity of flow in furrows.

In future studies at Columbia, Mo., emphasis will be placed on securing additional data from models.

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[1] S_1 - Irrigation shape furrow (20-inch flatbottom 1.5:1 side slope).
[2] S_2 - Conventional shape furrow.

ESTIMATING RATE OF ADVANCE FOR IRRIGATION FURROWS [1]

by

John R. Davis [2]

The design and evaluation of furrow irrigation systems depend in part upon the rate at which water flows from the upper end of a furrow to the lower end. Knowledge of this rate of advance for various rates of flow permits the designer or irrigator to select the proper length of run or rate of flow to achieve some uniformity of water distribution with a minimum of erosion. Procedures for determining rate of advance and evaluating furrow irrigation systems have been outlined by Criddle, et al. [3] and in several Soil Conservation Service Regional Engineering Handbooks.

Although the field evaluation of an irrigation system is a valuable tool, a mathematical expression of rate of advance also has some definite advantages. It might not only allow a designer to estimate rate of advance before the system is constructed but would also permit a study of the factors upon which rate of advance is dependent and would serve to point out current deficiencies in research data.

Some attempts have been made to derive expressions for rate of advance, particularly for irrigation borders. Lewis and Milne [4] derived a rather complex equation for rate of advance in borders, assuming an estimated depth of water and a predetermined functional relationship for infiltration. The effects of slope and surface roughness are not readily discernible but are reflected in the estimated depth of flowing water.

Israelsen [5] presented a simplified approach to border analysis, assuming a constant infiltration rate and a uniform depth of flowing water, which introduces some errors, depending on the soil. Hall [6], however, developed an equation that considers a variable infiltration rate and nonuniform depth of water, the latter reflecting the slope and hydraulic roughness of the soil surface. Hall uses a simple numerical method -- illustrated in his paper -- that appears to be fairly accurate.

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[1] Contribution from the California Agricultural Experiment Station, University of California, Davis.

[2] Lecturer and Associate Irrigation Specialist, Irrigation Department, University of California, Davis.

[3] Criddle, Wayne D., Sterling Davis, Claude H. Pair, and Dell G. Shockley. Methods for evaluating irrigation systems. Soil Conservation Service, U. S. Department of Agriculture, Agriculture Handbook No. 82, 1956.

[4] Lewis, M. R., and W. E. Milne. Analysis of border irrigation. Agr. Engr. 19:267-272. 1938.

[5] Israelsen, O. W. Irrigation principles and practices. Second Ed., John Wiley and Sons, New York. 1950.

[6] Hall, W. A. Estimating irrigation border flow. Agr. Engr. 37:263-265. 1956.

Bouwer [7] considered variable infiltration rates in his equations, which are solved simultaneously to determine field infiltration rates in borders. Some errors could be present if infiltration rates changed rapidly with time and if the nonuniform depth of water were not considered. The method offers some advantages in its simplicity and may be quite valuable for determining infiltration rates in irrigation furrows. Ostromechki [8] reviewed equations proposed by Skotnicki, Zakaszewski, Kostiakow, and Michalowski, which dealt with the calculation of the time required to flood irrigation checks. He proposed a differential equation for the time of flooding based on a variable rate of infiltration -- a method similar to Hall's. However, he apparently assumed that the water flowed into the lower end of the check and filled the check with successive increments of water depth. This premise deviates considerably from field practice and may result in a considerable error in the calculation of the volume of water stored in the border above the soil surface. He did not validate the equation with any empirical field studies.

Rational approaches to furrow irrigation have not received the attention that borders have, perhaps because of the complexity of most furrow systems. Several Australian workers contributed to studies on furrow irrigation in designating what they term a "primary flow" system. Lyon and Pennefather [9], Vasey [10], and Philip [11] present an equation for a primary flow system which relates the depth of water applied, the flow rate, and time of application; but the equation is based upon field trials and is not a basic mathematical approach to the entire system. The most recent rational approach for furrows was developed by Oroszlany and Wellisch [12] and actually employs a field trial requiring an application of 1 liter per second and a determination of the time required for the water to travel 50 meters. Then, by using a table prepared by these authors, one may find the flow rate and total time of application corresponding to the actual length of furrow and depth of water to apply. Some of their assumptions are not clear to the author, however, and some doubt is raised as to the validity of their solutions.

The fact that infiltration rates are a variable function of time must be considered in any equation which is to be employed for the determination of rate of advance in furrows or borders. Also, the water surface profile, hydraulic roughness, and channel shape must be included for determining the storage of water in the channel above the soil surface. Of all the methods and equations proposed for evaluating flow in borders or furrows, Hall's approach appears to meet these requirements and to offer the most promise as an accurate, simple solution. Also, because the derivation of his equation is based on mass conservation, it may be considered mathematically correct. Evaluation of only the component parts of the equation is required.

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[7] Bouwer, H. Infiltration patterns for surface irrigation. Agr. Engr. 38:662-669, 676. 1957.

[8] Ostromechki, Jerzy. On the computation of check flooding irrigation. Gospodarka Wodna, XIII:93-98, 133-136. 1953. (Translated from Polish).

[9] Lyon, A. V., and R. R. Pennefather. Furrow irrigation of community settlements. Jour. of the Council for Scientific and Industrial Research 19:38-45. 1946.

[10] Vasey, G. H. Notes on a new approach to furrow irrigation. Mimeograph, University of Melbourne, Australia. July 10, 1951.

[11] Philip, J. R. Some aspects of furrow irrigation. Mimeograph, October 1947.

[12] Oroszlany, I., and P. Wellisch. Edude envue d'assurer la precision en employant la methode de l'irrigation en la raie. Reports for Discussion, Third Congress on Irrigation and Drainage, Part I:8.45-8.67. 1957.

Hall's equation, with some modifications, was thus selected for describing furrow flow. In the following discussion, an equation for estimating rate of advance in furrows will be outlined and comparisons with field observations will be made.

DERIVATION OF EQUATION

When water flows into a furrow at a rate of Q cubic feet per second, part of this volume of water enters the soil at an intake rate $y = y\ (t)$, a function of time after wetting. The rest of the water fills a volume V_s above the soil surface in the furrow channel. For a given hydraulic roughness, furrow shape, and water surface slope at the head of the furrow, a depth of water d_o will be reached such that the rate of flow down the furrow at the head end is equal to the inflow rate Q.

The relationship between total infiltration $y = y\ (t)$ and V_s is given by the curves in figure 1 with time as a parameter. Downward from a horizontal line representing the soil surface, a series of points are plotted on a vertical axis, representing to scale the total volume of infiltration at the end of successive, equal increments of time. If it can be presumed that the infiltration characteristics are uniform for the length of the furrow, the horizontal lines then represent the total volume of water in the soil at the corresponding instants in time after water reaches the point considered. At the end of the first time increment, Δt, water will have reached X_1 and the volume of water applied at $X = 0$ will be y_1. At the end of the second time increment, the volume of water in the soil at $X = 0$ will be y_2, and the water surface will have reached X_2. The area between any two successive curves then represents the total volume of water applied to the soil during the time interval Δt.

In addition to the volume of water stored in the soil, there is a storage of water represented by the depth of water in the furrow. Depending on slope, roughness, and shape of the furrow, there is a minimum depth d_o necessary at the head of the furrow to pass the flow Q down the furrow. This depth may be obtained directly from Manning's equation or from flow equations that may be developed later to more adequately describe the flow phenomena in small, rough channels.

The depth of flow necessary for flow past successive points down the furrow will decrease, however, since the total flow past these points decreases. The water depth thus becomes a function of the distance down the furrow. While the depth of water at each point could be computed, a simpler and more general approach was to assume that the type of function represented by the water surface was the same at all instants of time. With this assumption, the ratio of the actual volume of surface storage to the volume of the circumscribing parallelopiped is a constant c, which from reasoning should be greater than one-half but less than one.

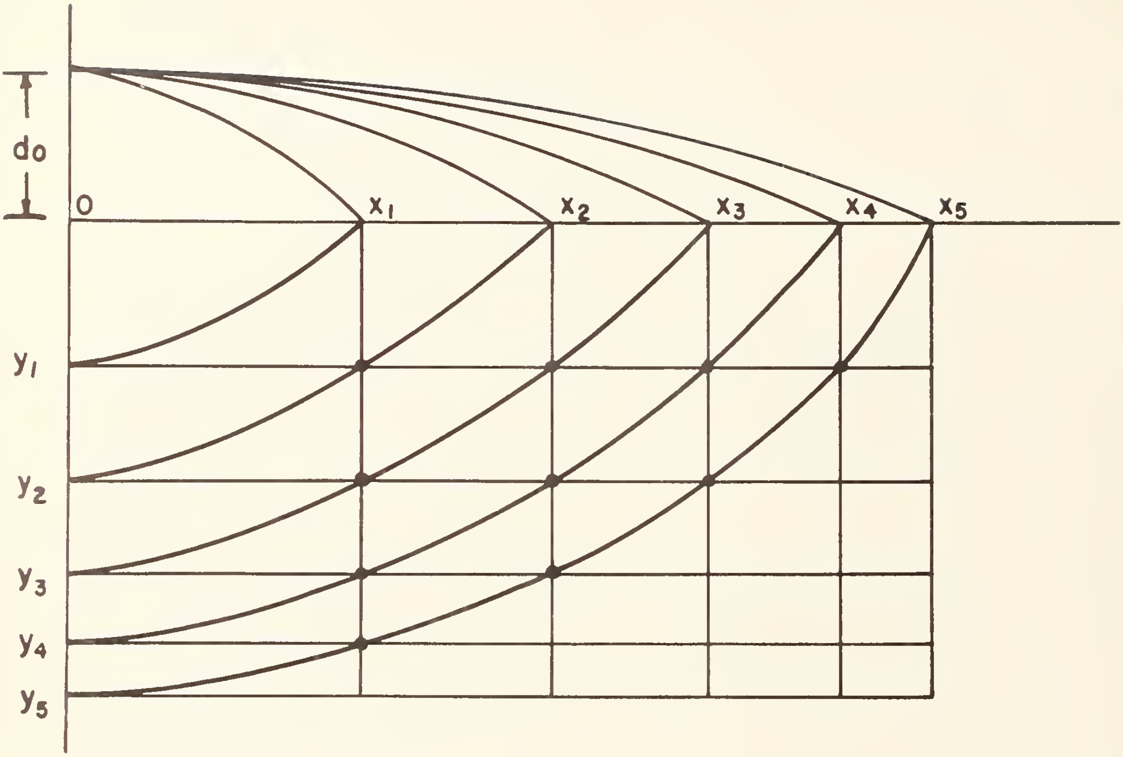

Figure 1.--Schematic illustration of the relation between total infiltration, surface storage, and distance down a furrow.

The value of c would depend not only on the shape of the water surface but also on the shape of the furrow. For example, if the equation of the water surface happened to be a cubical parabola with vertex on the X-axis at the point in question, the value of c is 0.75 for a rectangular-shaped furrow; 0.375 for a triangular-shaped furrow; and 0.321 for a semicircular-shaped furrow.

The volume of water calculated in the above manner is only that which is necessary for a required flow to occur at the roughness and slope of the channel and does not include the volume of water that must be applied to fill the minor surface depressions before flow can occur. Thus, a correction must be applied to represent the volume of water that would remain in the furrow after the water is turned off, assuming zero infiltration. This average volume correction was termed the puddle factor, denoted by the symbol e. It is somewhat dependent upon surface roughness and land grading accuracy but, for most soil conditions, should be a fairly constant value.

The volume of water in storage above the soil surface at any time t_i is then equal to

$$V_{si} = \left[c \cdot f(d) + e \right] X_i \tag{1}$$

The increment of surface storage volume which occurs during any time interval is equal to the difference between the surface storage volumes at the beginning and end of the time interval.

Thus

$$\Delta V_{si} = \left[c \cdot f(d) + e \right] \Delta X_i \tag{2}$$

The increment of the volume of water stored in the soil is equal to the area between two successive total application curves. In figure 1, for the fifth time increment, this is the area whose corners are y_4, X_4, X_5, and y_5. The area except the last three-cornered element below ΔX_5 can be determined by the trapezoidal rule. This last element can be estimated in the same manner as the surface volume by assuming that the shape of the curve in this last element is constant. The ratio of the actual area under ΔX_i to the area of the rectangle circumscribing it will be a constant, k, whose value should lie between one-half and one.

The increment of volume of water applied to the soil, ΔV_{ai} is then given by

$$\begin{aligned} \Delta V_{ai} = {} & 1/2 \left[(y_i - y_{i-1}) + (y_{i-1} - y_{i-2}) \right] \Delta X_1 + \\ & 1/2 \left[(y_{i-1} - y_{i-2}) + (y_{i-2} - y_{i-3}) \right] \Delta X_2 + \ldots + \\ & 1/2 \left[(y_2 - y_1) + (y_1 - 0) \right] \Delta X_{i-1} + k\, y_1\, \Delta X_i \end{aligned} \tag{3}$$

To simplify the above equation, one may assume in most cases that the infiltration function $y = at^n$ is applicable. In fact, as long as y is an algebraic function of t (i.e. nontrigonometric or transcendental), this postulate does not affect the validity of the resulting equation; it is merely a more simplified form.

Then assuming that $y_1 = a(\Delta t)^n$; $y_2 = a(2\,\Delta t)^n$; $y_3 = a(3\,\Delta t)^n$; $y_i = a(i\,\Delta t)^n$,

$$\begin{aligned} \Delta V_{ai} = {} & 1/2 \left[a(i\,\Delta t)^n - a\left\{ (i-2)\,\Delta t \right\}^n \right] \Delta X_1 + \\ & 1/2 \left[a\left\{ (i-1)\,\Delta t \right\}^n - a\left\{ (i-3)\,\Delta t \right\}^n \right] \Delta X_2 + \ldots + \\ & 1/2 \left[a(2\,\Delta t)^n \right] \Delta X_{i-1} + k\, a(\Delta t)^n\, \Delta X_i \end{aligned} \tag{4}$$

Simplifying this equation by factoring, then

$$\Delta V_{ai} = \frac{a(\Delta t)^n}{2} \left[\left\{ i^n - (i-2)^n \right\} \Delta X_1 + \right.$$

$$\left\{(i-1)^n - (i-3)^n\right\} \Delta X_2 + \ldots + 2^n \Delta X_{i-1} + 2 k \Delta X_i \Big] \quad (5)$$

By substituting a factor defined by

$$g_i = i^n - (i-2)^n \qquad \text{where } i \geq 2,$$

$$\Delta V_{ai} = \frac{a(\Delta t)^n}{2} \left[g_i \Delta X_1 + g_{i-1} \Delta X_2 + \ldots + g_2 \Delta X_{i-1} + 2 k \Delta X_i \right] \quad (6)$$

By the law of conservation of matter, the quantity of water flowing into the furrow during any time increment must be equal to the sum of the increments of storage produced. The mass balance for the furrow during any time increment is then, for $i \geq 2$;

$$Q (\Delta t) = \frac{a(\Delta t)^n}{2} \left[g_i \Delta X_1 + g_{i-1} \Delta X_2 + \ldots + g_2 \Delta X_{i-1} + 2 k \Delta X_i \right] + \left[c \cdot f(d) + e \right] \Delta X_i \quad (7)$$

Presuming that the shape of the furrow is either parabolic or V-shaped, the volume of water in surface storage can be expressed as a function of d_o^2. Also, since the infiltration function is likely to be characterized by cylinder or furrow infiltrometer techniques, or by inflow-outflow data for a relatively long length of furrow, the infiltration function should be modified by a factor F to permit the use of the equation for all conditions of furrow shape, spacing, and depth of water. This latter modification is based upon the results of Rowe 13/ and Nagmoush 14/.

The resulting equation, including these modifications and with some rearranging, becomes

$$\Delta X_i = \frac{Q (\Delta t) - \frac{F\, a(\Delta t)^n}{2} \left[g_i \Delta X_1 + g_{i-1} \Delta X_2 + \ldots + g_2 \Delta X_{i-1} \right]}{F\, a(\Delta t)^n k + c d_o^2 + e} \quad (8)$$

For X_1 the solution is simply

$$\Delta X_1 = \frac{Q (\Delta t)}{F\, a(\Delta t)^n k + c d_o^2 + e} \quad (9)$$

13/ Rowe, P. P. Moisture movement in furrow irrigation. M.S. Thesis, Washington State College, Department of Agronomy. 1952.

14/ Nagmoush, S. R. Effect of sources pressure, initial moisture content and dimensions of flow on infiltration. M.S. Thesis, Washington State College, Department of Agronomy. 1956.

The value of ΔX_1 is obtained from equation (9) and substituted into equation (8) for i = 2 to obtain ΔX_2. This value is substituted in turn in equation (8) for i = 3 to obtain ΔX_3.

The g_i are calculated directly from the empirical total infiltration function and can be shown for various values of n in tabular form. While not necessary, the solutions of equation (8) can be determined easily with computers or with the form shown by Hall in his paper.

Equation (8) is simpler than it may appear, for if a constant time interval Δt is used, the first term of the numerator and the denominator remain constant for all calculations. Also, if a table for values of g as a function of n is prepared, the calculations move rather speedily.

CALCULATING RATE OF ADVANCE

The equation for rate of advance contains several unknown terms, namely F, k, c, e, and ΔX_i. For the analyses of field data, the puddle factor e was assumed to lie within the range of 0.001 to 0.003 cubic foot per foot. Errors in this estimation should not affect the accuracy of the equation significantly. The value of k, which is used to express the volume of water in storage in the soil for the length ΔX_i, was assumed equal to unity, which involves a rather small error tending to decrease the calculated rate of advance. Calculations of this error showed, however, that it was insignificant.

Only the functions F, c, and ΔX_i in the equation remain unknown. Thus, for each flow measurement for each of the field studies described later, values for F and c were assumed and the ΔX_1 and ΔX_2 calculated. By trial and error, values of F and c were finally selected such that the calculated values of ΔX_1 and ΔX_2 agreed with the measured values. Once this initial step was performed, the calculations for the remaining ΔX_i proceeded rather speedily, for the denominator of the equation and most of the numerator remained constant.

This procedure was necessary in these analyses because so little is known of the hydraulic roughness of furrows and the infiltration characteristics of furrows. As additional research evaluates these parameters, this first trial and error step will become unnecessary, and appropriate values of F and c may be determined before the calculations proceed.

The time Δt selected for the calculations of rate of advance was either 10 or 20 minutes, depending on the length of time the field measurements were made. For eight of the trials, two separate calculations using 10- and 20-minute intervals were made. There was no difference in the rate of advance due to these different time intervals.

FIELD STUDIES

Field studies were conducted in 1958 near Visalia, Calif., on Cajon fine sandy loam and at Davis on Yolo silty clay loam, to gather data to verify the application of equation (8). For the studies at Visalia, two separate fields of cotton were selected, one with an average grade of 0.2 percent, the other with an average grade of 0.09 percent. In each case, water was supplied to each furrow through siphons or spiles from a head ditch, and the flow rates were measured volumetrically. Trials were made during the first, third, and fifth irrigations after the preirrigation, using five furrows for each of about five flow rates. The trials at Davis were conducted during the first and second irrigations of sorghum on a field with 0.2 percent grade, using four furrows for each of three rates of flow. Water was delivered through gated pipe and measured volumetrically.

For each trial, two furrow infiltrometers, as described by Bondurant [15], were installed on adjacent furrows during the irrigation. Data from stage recorders were converted and plotted to obtain the infiltration function, which, in all cases, approximated an equation of the form $y = at^n$. Because so little is known about the hydraulic roughness of a furrow, the depth of water at the head end of the furrow was measured, and after each irrigation, measurements of furrow cross sections were made. Rate of advance was determined for each furrow in 50-foot intervals.

COMPARISONS OF OBSERVED AND CALCULATED RATE OF ADVANCE

Comparisons of calculated rate of advance and observed rate of advance for some of the field studies are shown in figures 2 through 6. Figure 7 shows a similar comparison, based on data from an extension training conference at Davis, Calif., in 1950. These latter data include only inflow-outflow and rate of advance measurements in furrows for each of three flow rates.

In all cases, the equation predicted the rate of advance of the waterfront fairly accurately. The equation performed well with rather limited data and was also applied quite satisfactorily to fields of nonuniform slopes or slightly irregular slopes. Although a number of simplifying assumptions were made, the fact that the predicted rates of advance were similar to those observed indicates the inherent accuracy and reliability of the equation.

PERFORMANCE OF FURROW INFILTROMETERS

Assuming that the rate of advance equations are valid, the factor F should represent some measure of the infiltration phenomenon in flowing furrows in comparison to that in the furrow infiltrometer. Ratios of depth of water in the flowing furrow to the depth of water in the furrow infiltrometer were calculated and plotted against the factor F that was found to result in a fairly

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[15] Bondurant, J. A. Developing a furrow infiltrometer. Agr. Engr. 38:602-604. 1957.

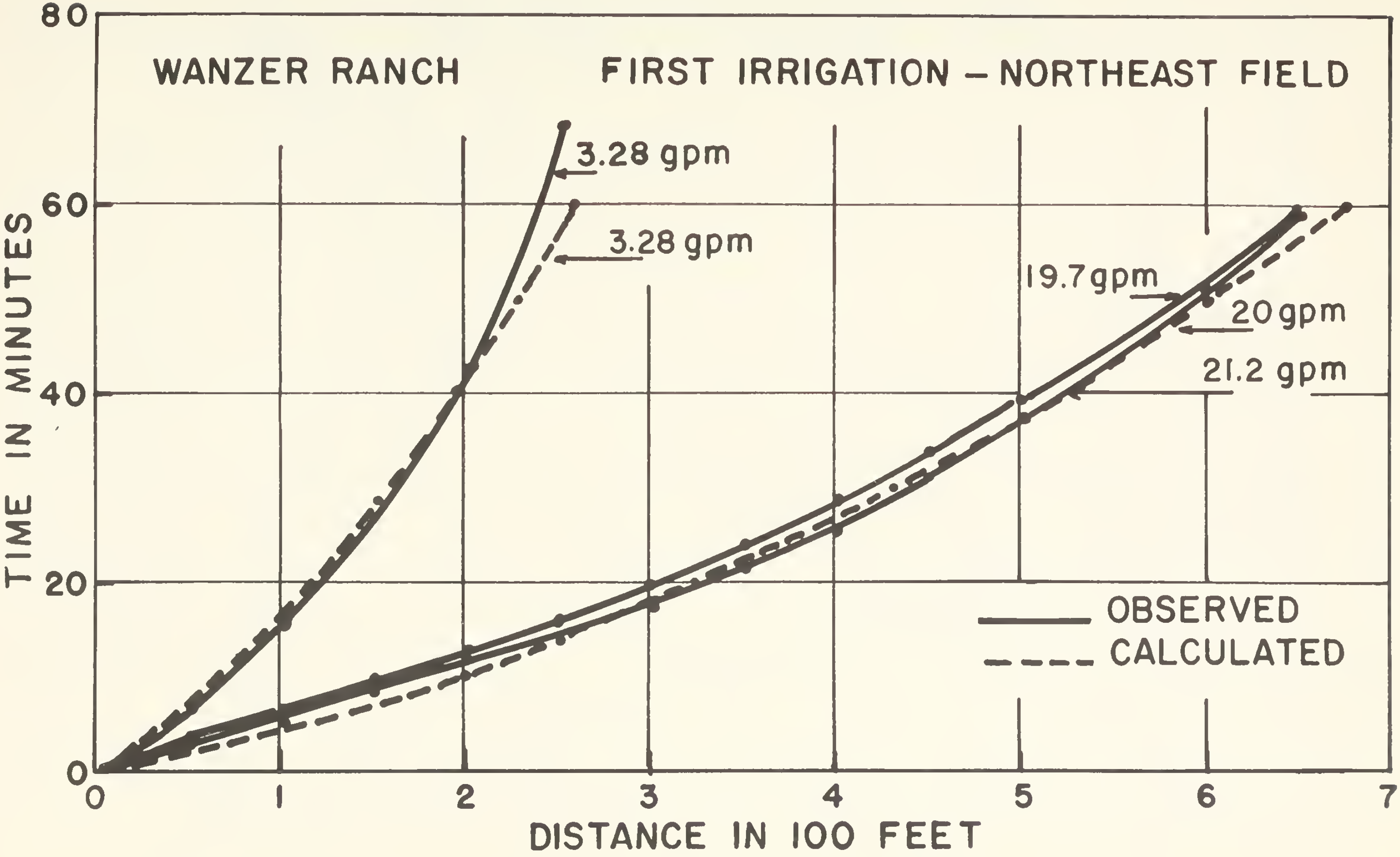

Figure 2.--Comparisons of observed and calculated rates of advance of water in furrows in Cajon fine sandy loam.

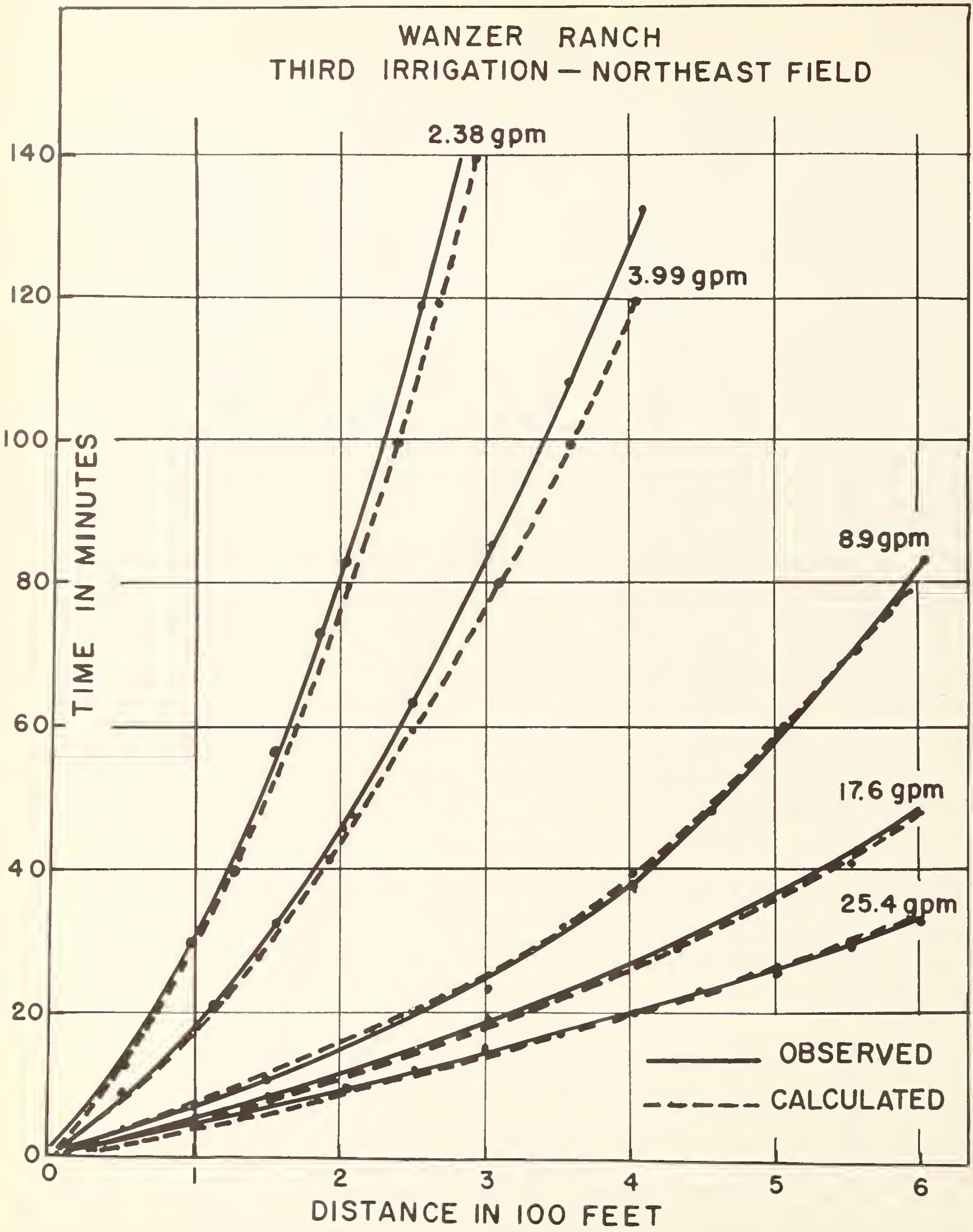

Figure 3.--Comparisons of observed and calculated rates of advance of water in furrows in Cajon fine sandy loam.

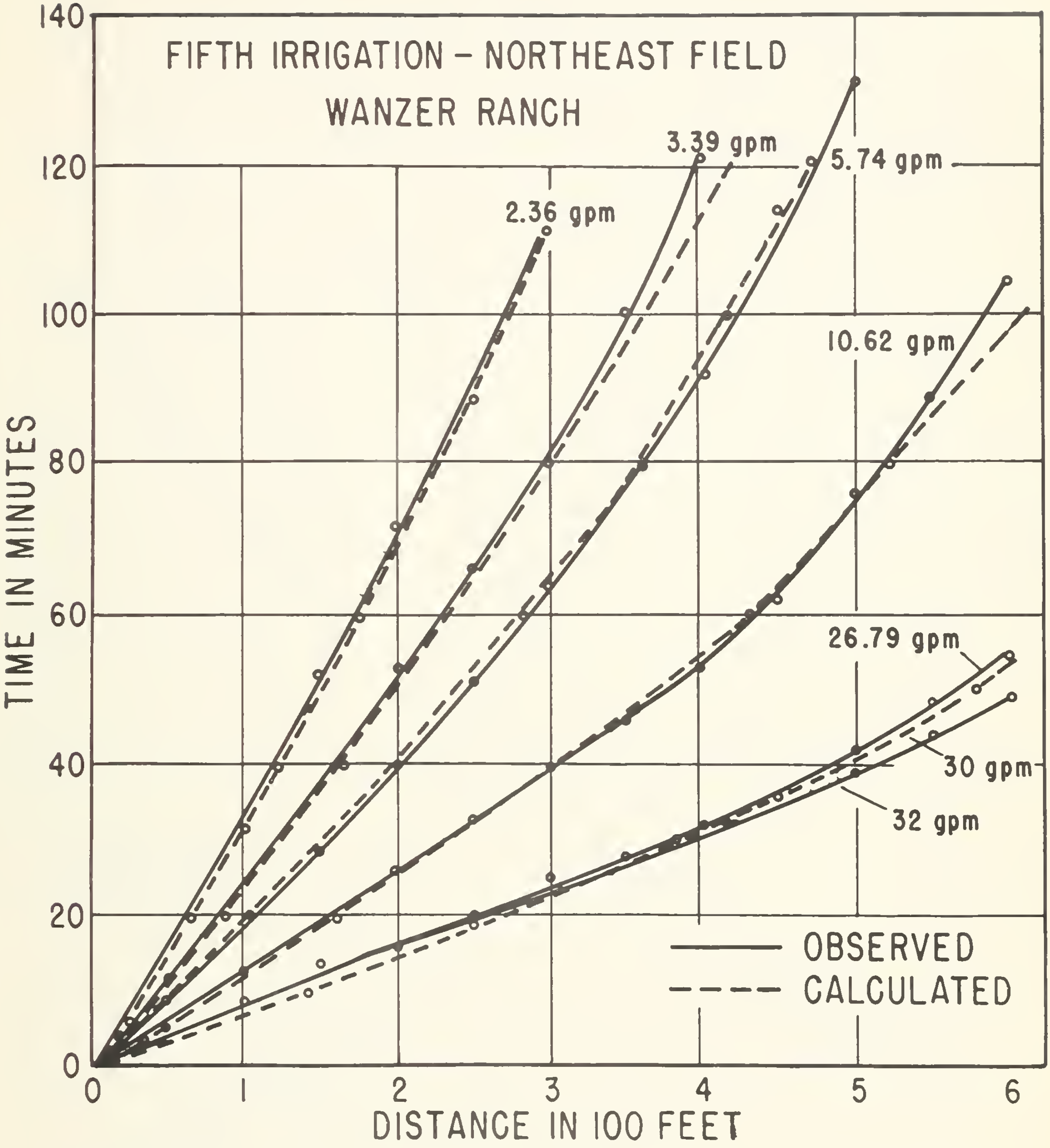

Figure 4.--Comparisons of observed and calculated rates of advance of water in furrows in Cajon fine sandy loam.

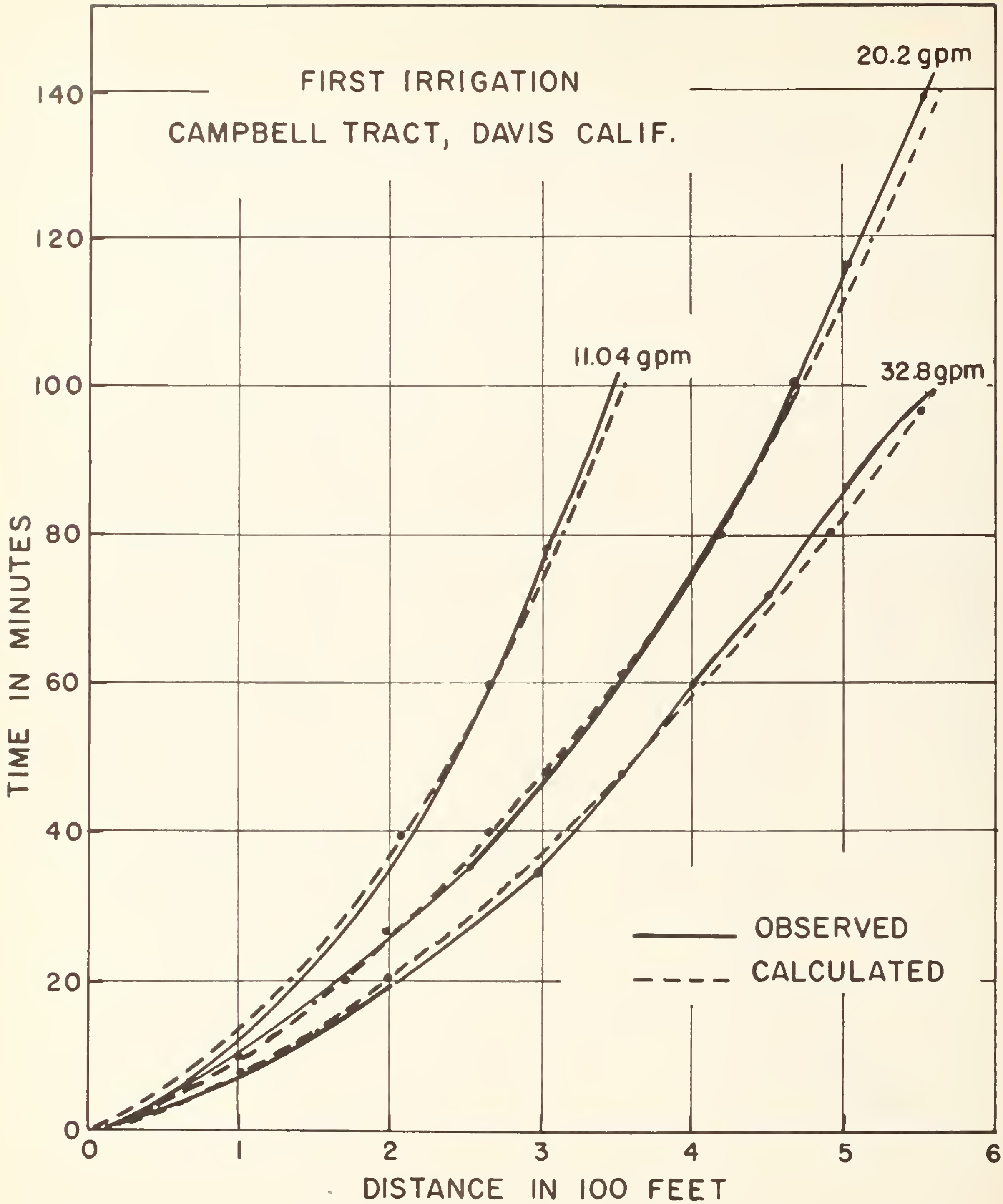

Figure 5.--Comparisons of observed and calculated rates of advance of water in furrows in Yolo silty clay loam.

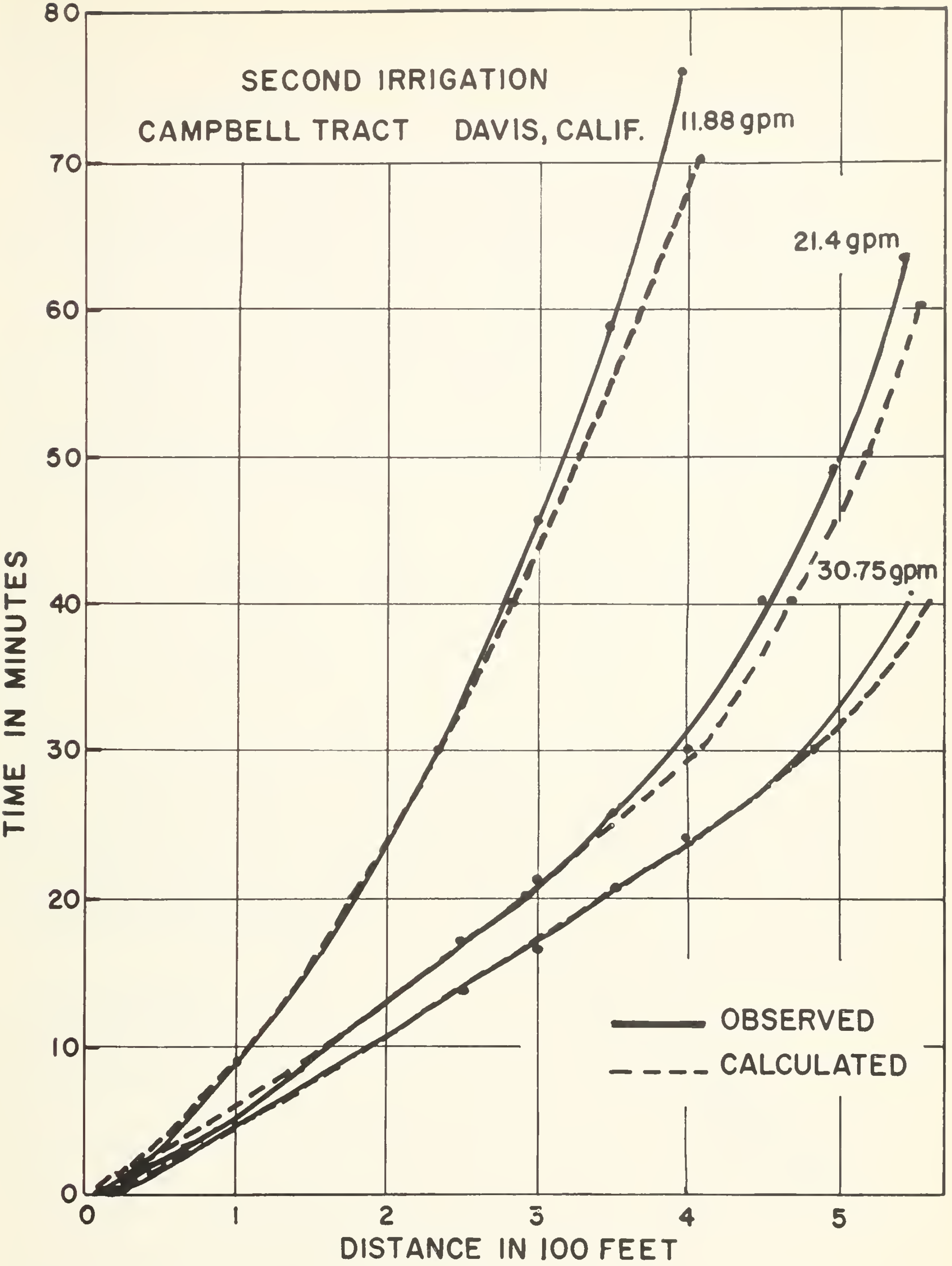

Figure 6.--Comparisons of observed and calculated rates of advance of water in furrows in Yolo silty clay loam.

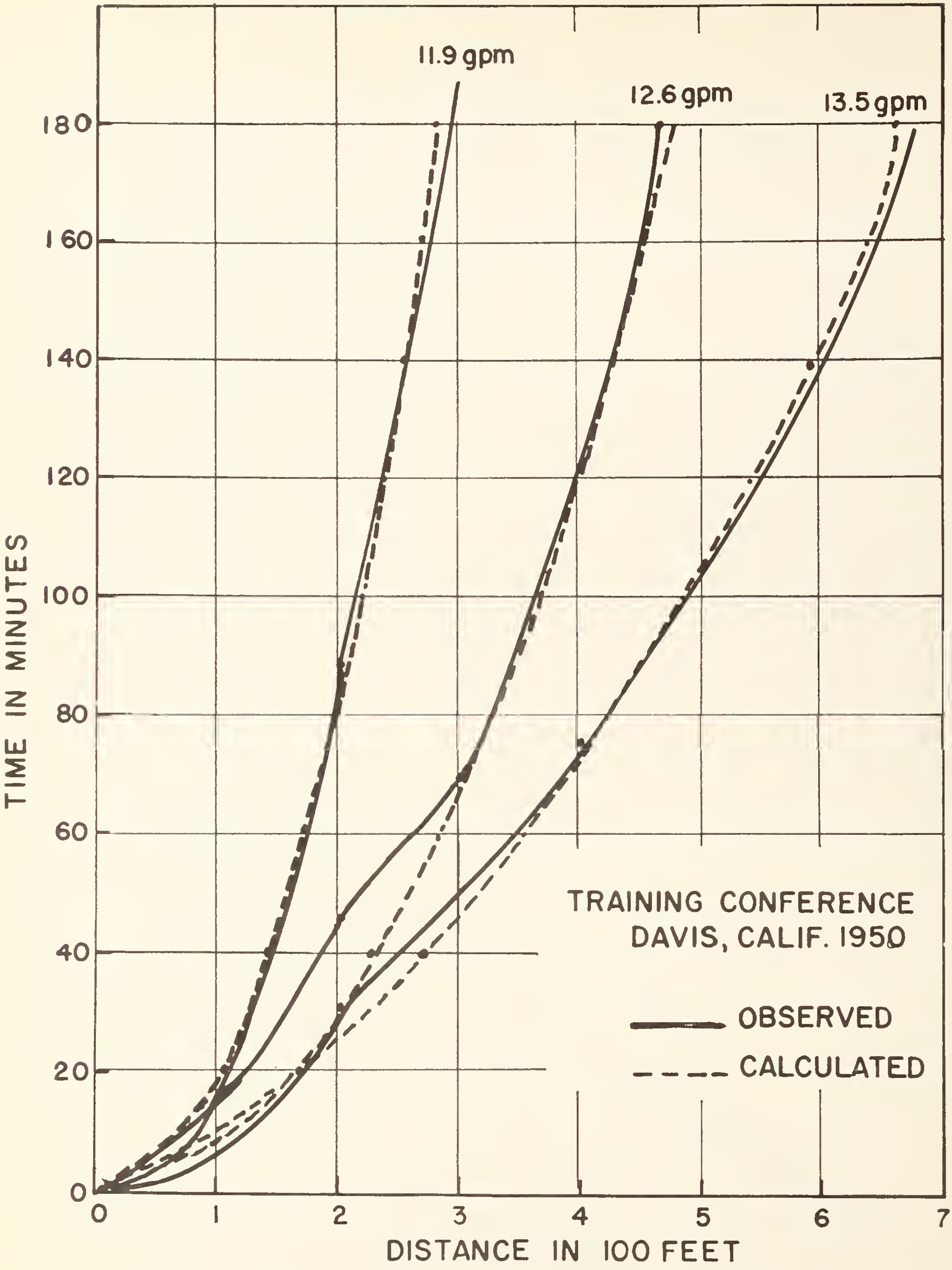

Figure 7.--Comparisons of observed and calculated rates of advance of water in furrows in Yolo silty clay loam.

accurate rate of advance prediction. This relation is shown in figure 8. It is evident that as the depth of water in the furrow increased in relation to the depth of water in the infiltrometer, the value of F also increased. In all cases, the infiltration rate in the flowing furrow was equal to or less than the infiltration rate measured in the infiltrometer.

If F was a reliable measure of actual furrow infiltration rates, these data also indicated that the condition of the furrow (time of season) had a considerable bearing on the relation of the infiltration rates in the furrow to that in the infiltrometer.

Although these data are not complete and should be considered rather inconclusive, it appears probable that the infiltration rate of a furrow is related to that measured by the infiltrometer; but that the relationship is affected greatly by the ratio of the water depths and the textural and structural condition of the soil in the furrow. Additional work will certainly be necessary before the furrow infiltrometer can be used to accurately predict the infiltration from a flowing furrow. For quantitative purposes, it appears that many factors must be considered.

HYDRAULIC ROUGHNESS OF IRRIGATED FURROWS

A part of the studies on furrow flow was devoted to another phase of the rate of advance phenomenon -- that of surface storage in the furrow, which presumably is a function of hydraulic roughness.

The relation between roughness and flow velocity may possibly be expressed in a manner similar to the expressions for friction in pipes as a function of Reynolds number. In furrows, the roughnesses are sufficiently large in relation to furrow depth to warrant such an approach. However, at high velocities, the flow tends to smooth the furrow and dissipate the cloddiness, which reduces the roughness of the furrow. On the other hand, high flow rates may tend to alter the shape of a furrow to a generally less efficient hydraulic cross section.

Thus, the flow regimes in irrigation furrows are extremely varied and are rather difficult to evaluate. Attempts were made, however, to determine the hydraulic roughness of furrows under assumed steady flow conditions. After water had been flowing in a furrow for an appreciable length of time, the depths of water at each end of a 50-foot length of furrow were marked. After the water was shut off, measurements of area, wetted perimeter, and slope were made. These data were collected for various flow rates in replicate, and hydraulic roughness was then calculated from Manning's equation.

The results of the analysis for Yolo silty clay loam are shown in figure 9, which expresses the calculated n as a function of furrow velocity for two irrigations. Because the same relationship apparently existed for the second irrigation as the first, it appears that the aggregates in the furrow either no longer existed or had already stabilized by the time of the second irrigation, and that the increased growth of the sorghum crop had no effect on the roughness.

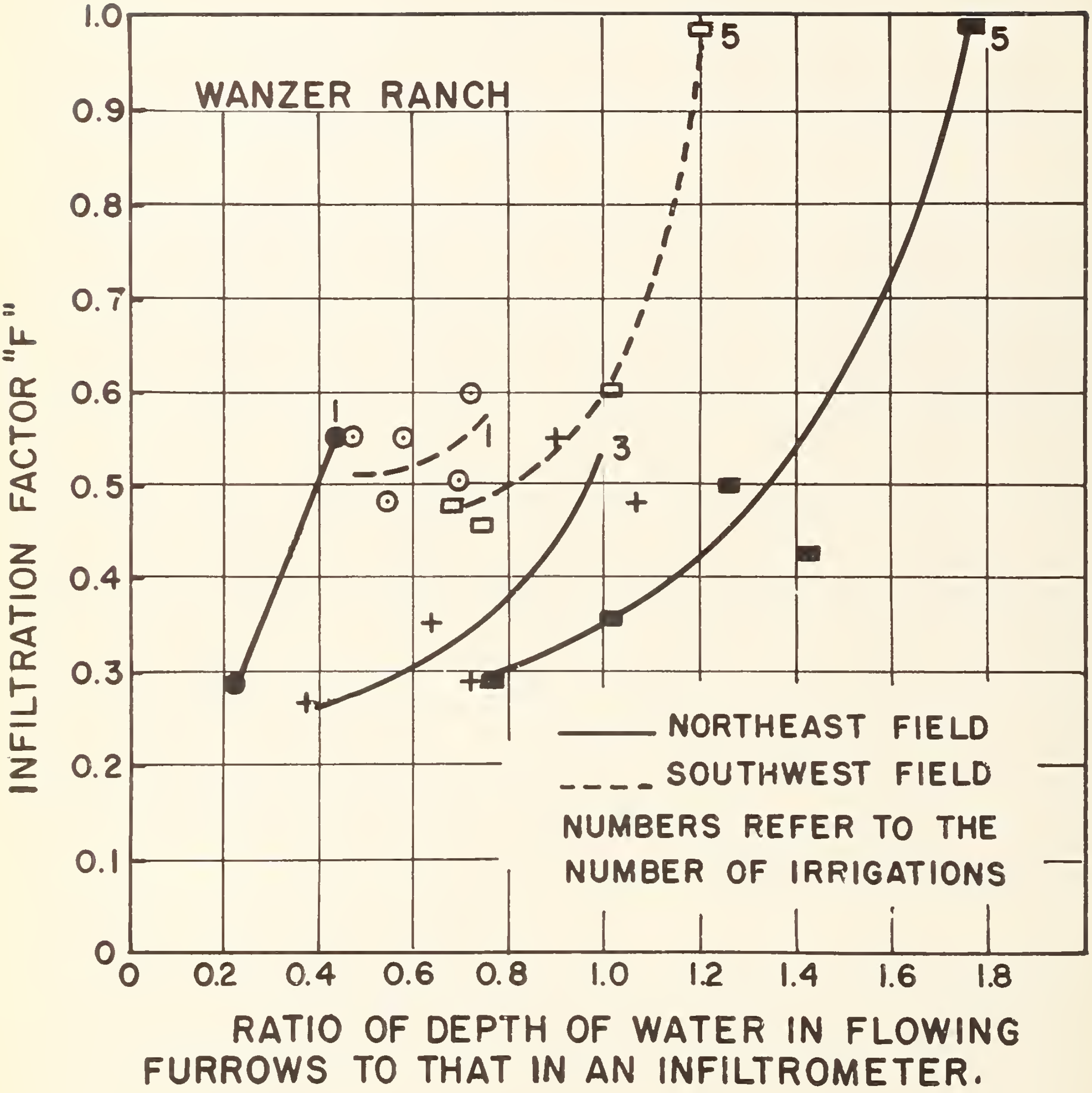

Figure 8.--Relation between the ratio of depth of water in a furrow infiltrometer to the depth of water in a flowing furrow and infiltration factor F, showing seasonal variability.

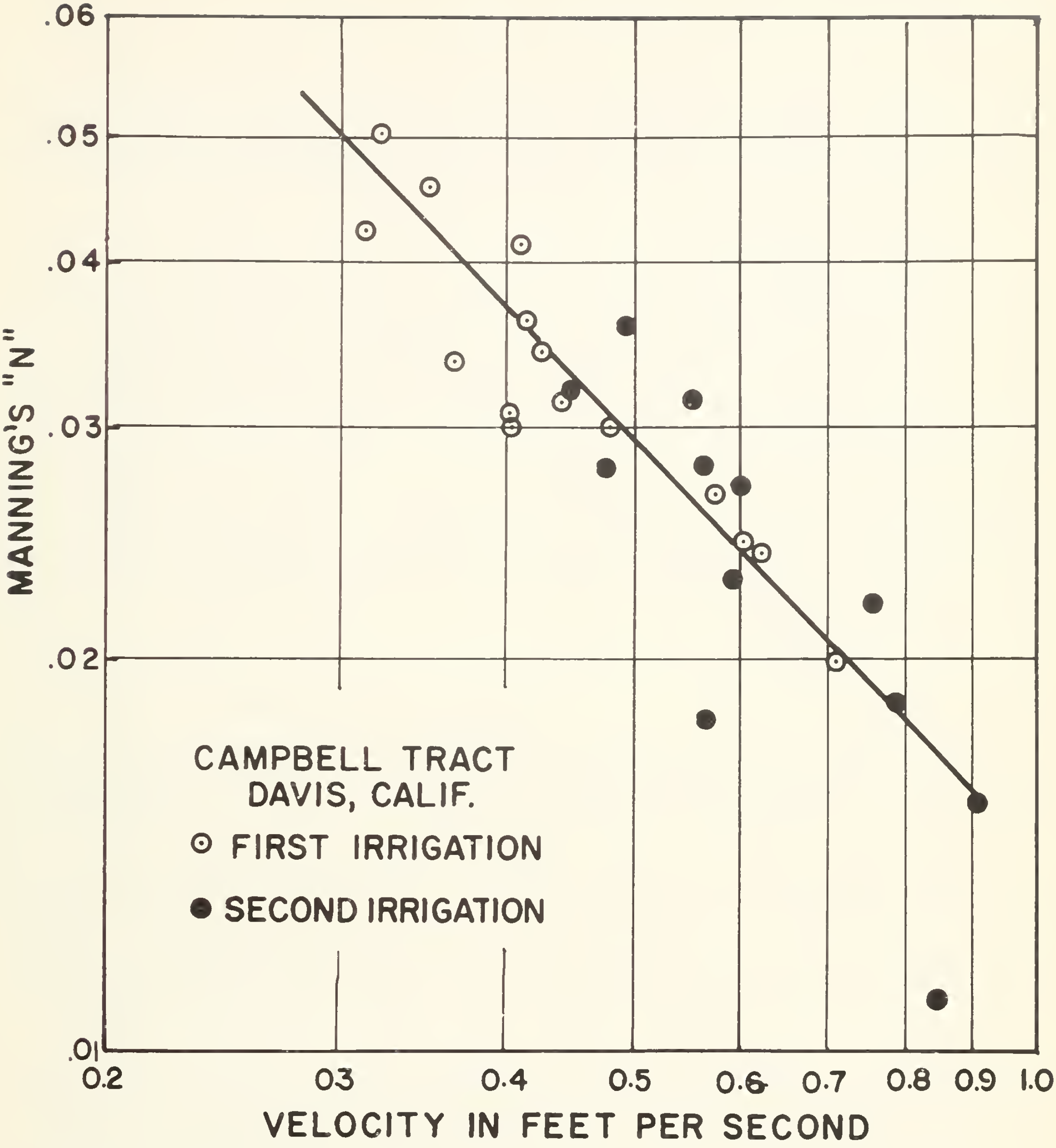

Figure 9.--Relation between velocity of water in furrows and Manning's roughness coefficient, for Yolo silty clay loam.

It appears evident that the hypothesis expressed earlier was correct; that the hydraulic roughness is a function of flow velocity, such that as the velocity of flow increased, the roughness coefficient decreased. This is evidently due to a smoothing of surface irregularities in the furrow.

The relationship in figure 9 can be expressed in the form $n = cv^{-1}$. If this expression is substituted into Manning's equation and considering that the grade is constant, then the hydraulic radius was also constant. This conclusion infers that hydraulic radius was independent of the velocity and that soil conditions were such that a constant relation between area and wetted perimeter existed for all flow rates.

The results for the Cajon fine sandy loam are shown in figures 10 and 11, which express the relations between calculated n and flow velocity and flow rate. These results are approximately the same as those above except that the slope of the lines is different. Here, two equations can be expressed: $n = cv^{-0.75}$, $n = BQ^{-0.33}$. Substituting each of these equations into Manning's equation and assuming a known grade, these two equations may then be solved simultaneously for the area and hydraulic radius for any given flow rate.

These results and conclusions would certainly not apply to other soils but indicate that some relationships may exist which will permit a reasonably accurate determination of the volume of water in surface storage in a furrow. Additional studies are necessary before any such relationships can be developed, however.

SUMMARY

The final merits of the rate of advance equation will be judged by its applicability to project planning, systems designs, and systems analysis. Its accuracy will be governed by the accuracy of data used in the calculations.

The time required for the computations is quite small compared to field evaluations, and the fact that the equation appears workable indicates that computer analyses may become possible. Also, the equation appears to possess several advantages over some of the others proposed, in that infiltration rates and hydraulic roughness parameters that change with time and season can be considered.

If indications of erosion hazard are available, this equation should serve well to provide a sound basis for the evaluation of potential irrigation efficiency. At the present time, it has already served as a basis for the evaluation of areas of deficient research accomplishments and for a better understanding of the relative influence of parameters affecting furrow flow.

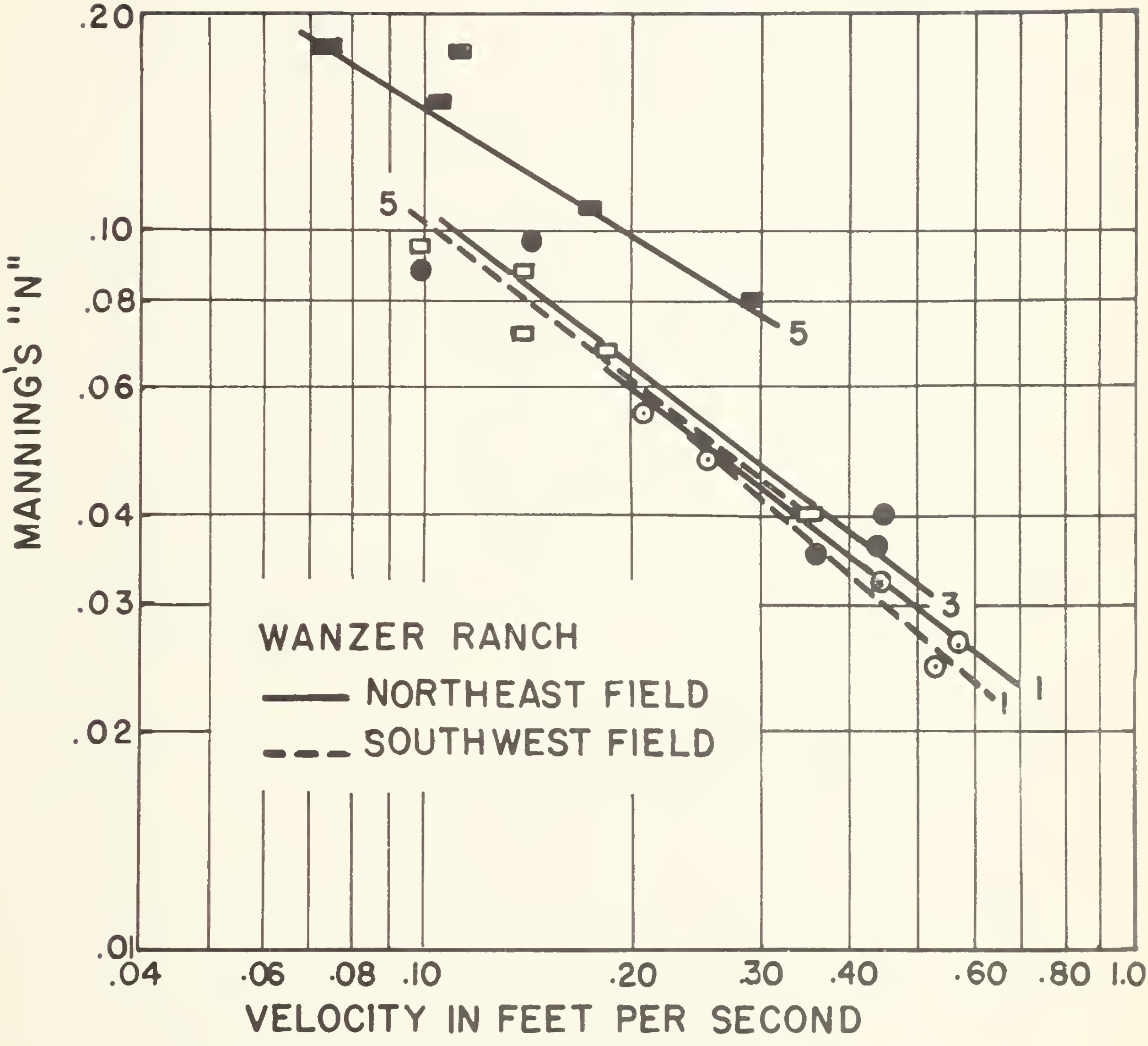

Figure 10.--Relation between flow rate in furrows and Manning's roughness coefficient, for Cajon fine sandy loam.

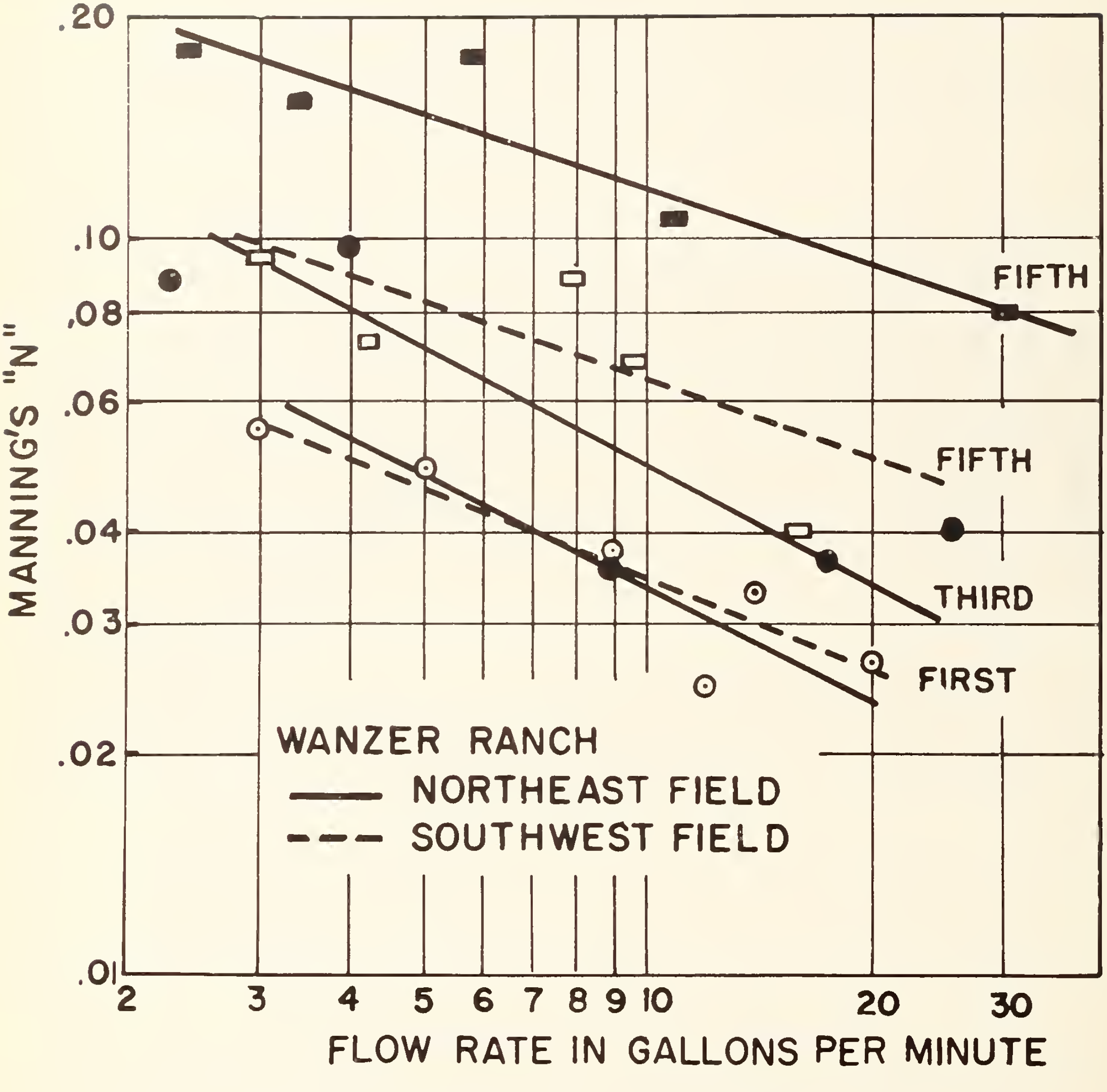

Figure 11.--Relation between velocity of water in furrows and Manning's roughness coefficient, for Cajon fine sandy loam.

HYDRAULICS OF SUBCRITICAL FLOW IN SMALL, ROUGH CHANNELS [1]

by

E. G. Kruse [2]

The design of surface irrigation systems involves extremely complex flow phenomena. Myers [3] stated that major errors can result from the use of flow equations that do not apply to the situation at hand. Basic research to develop equations applicable to flow in irrigation furrows is needed. The several dozen papers in the literature on flow in open channels do not treat the irrigation furrow case.

Powell [4] [5] studied flow in smooth and rough channels with sub- and supercritical flow regimes. Powell examined the effect of discharge, roughness and slope on the flow, but he states that other factors, such as the angle between channel sidewalls and bottom, need to be studied. Furthermore, Powell's studies did not include the extreme magnitude of relative roughness likely to be found in channels comparable to irrigation furrows.

Studies of laminar, transition, and turbulent flow over smooth and pitted beds were made by Parsons [6]. Parsons developed a modification of the laminar flow equation to represent disturbed viscous flow.

Sayre [7] studied the effect of spacing and pattern of roughness elements on subcritical flows. He used a single size of roughness element. A hydrodynamically rough boundary existed for all test runs. Sayre developed an equation relating the Chezy resistance coefficient to the relative roughness.

Morris [8] has derived relationships between the Darcy-Weisbach coefficient and different roughness forms depending on whether the channel and flow fall in the category of isolated roughness, wake interference, or quasi-smooth. Morris theorizes that the type of flow is largely dependent on the longitudinal spacing of the roughness elements.

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[1] Contribution from Soil and Water Conservation Research Division, Agricultural Research Service, U. S. Department of Agriculture, and Agricultural Engineering Section, Colorado State University, cooperating.

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[6] Parsons, D. A. Depths of overland flow. USDA-TP-82, July 1949.

[7] Sayre, William W. Artificial roughness patterns in open channels. Unpublished Master's Thesis, Colorado State University, March 1957.

[8] Morris, Henry M., Jr. Flow in rough conduits. Trans. Amer. Soc. of Civil Engr., Vol. 120, Paper No. 2745, 1955.

The hydraulics of flow in rough channels similar to irrigation furrows is being studied experimentally at Colorado State University. A 60-foot flume has been adapted for the study so that slope, boundary shape, boundary roughness, and discharge may be varied. The design of the flume will also permit infiltration to take place along the flow boundary at controlled rates.

The studies are in the initial stages; only very wide, rectangular channels have been considered. The studies will be continued to consider the effects of channel shape and infiltration through the channel boundary.

The objectives of the study are:

1. To relate some description (height, width, shape and/or spacing) of the random roughness elements to the resistance coefficient of the flow.
2. To determine the effect of furrow shape on the resistance coefficient.
3. To determine the effect of infiltration on the resistance coefficient.
4. To determine what roughness is formed in channels with erodible boundaries at low flow rates.

RESULTS

All tests that have been completed to date have been representative of infinitely wide, impermeable channels. Thus, channel shape and infiltration variations have not yet been considered. Discharges and slopes have been varied to give flows ranging from laminar to turbulent.

The first analysis of the data was to determine the variation of resistance coefficient with depth of flow for a given boundary condition. Figure 1 shows the relationship of Manning's n to depth of flow for rough and smooth boundary conditions. The rough boundary was created by drawing a blade under the surface of a damp, compacted, sandy soil. The smooth boundary was formed by troweling the sandy soil. Both boundary forms were sprayed with a water glass solution before the tests to prevent alterations in the boundary roughness during a series of runs. The upper curves of figure 1 indicate a large variation of n with depth of flow. For smooth channels this variation is much less evident. It is likely that relative roughness is an important factor in determining the resistance coefficient and at the low relative roughness of the smooth bed, a nearly constant n was attained. The divergence of the curves at low depths is due to laminar or transition flows in this region. A variation of n with channel slope is also evident.

The Manning n varied less than 10 percent for Reynolds numbers greater than 2000 with the bed smooth. For the rough bed, n varied with both slope and Reynolds number and approached a constant value asymptotically only at very high values of Reynolds number.

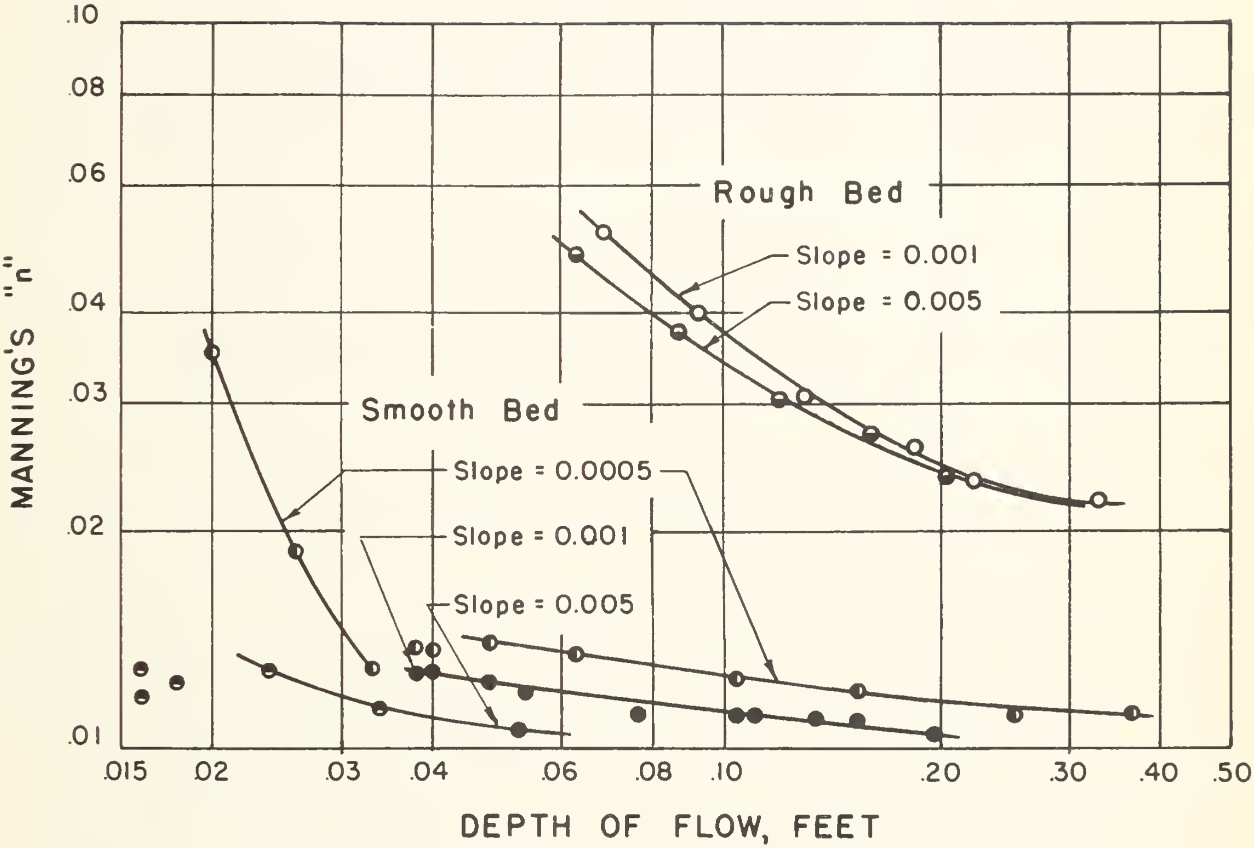

Figure 1.--Variation of resistance coefficient with depth of flow.

HYDRAULIC CHARACTERISTICS OF SURFACE RUNOFF FROM SIMULATED RAINFALL ON IRRIGATION FURROWS [1]

by

Norris P. Swanson [2]

INTRODUCTION

This is a progress report of a study initiated to meet water management research needs in Nebraska. This study was planned specifically to determine the maximum furrow grades permissible without excessive erosion, and the limitations on design of irrigation systems as influenced by erosion hazards due to rainfall.

The objectives of this study, insofar as furrows are concerned, are:

1. To determine the hydraulic characteristics of surface flow in individual irrigation furrows with runoff produced by simulated rainfall.

    (a) To determine the erosion characteristics (including velocity) of flows in furrows under rainfall runoff conditions.
    (b) To determine the safe capacities of furrows of various sizes as related to slope and length.
    (c) To determine roughness coefficients in the flow equation for furrows.
    (d) To determine the maximum lengths of runs as related to gradient in providing adequate drainage for unusable precipitation under various climate, soil, and cropping conditions.
    (e) To measure the time of concentration for furrows with various spacings, cross sections, and slopes.

2. To determine the conditions under which level irrigation may be employed and what runoff disposal facilities and limitations will be required under the various soil and crop conditions encountered.

3. To make recommendations for the design of runoff disposal systems for contour bench irrigation systems.

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[1] Contribution from Soil and Water Conservation Research Division, Agricultural Research Service, U. S. Department of Agriculture, Nebraska Agricultural Experiment Station, cooperating. Intended for inclusion as a progress report of this research.

[2] Agricultural Engineer, Western Soil and Water Management Research Branch, Soil and Water Conservation Research Division, Agricultural Research Service, U. S. Department of Agriculture at University of Nebraska, Lincoln.

4. Develop techniques of measuring the depth of flow and velocity of small streams in furrows and border strips.

PROCEDURE

Equipment was operated on a field site in 1957 but the first comprehensive data were obtained in 1958. Field work in 1958 included some nearly level furrows on the Soil Conservation District farm at Scottsbluff as well as graded furrows on the Scotts Bluff Experiment Station and on a farm in Seward County, about 30 miles west of Lincoln. Erosion was observed but not measured in the 1958 studies. In 1959, field studies were conducted in the Big Thompson Soil Conservation District (Loveland vicinity) in Colorado in cooperation with the Soil Conservation Service and in Webster County (south central) and Seward County in Nebraska. All of the 1959 studies were on furrows with erosive or near-erosive slopes.

The research techniques evolved now include several pieces of equipment, which will be enumerated.

1. An engine-powered, trailer-mounted, centrifugal pump is used to supply water under pressure. Suction can be taken from a portable pipeline, a farm pond, or from an irrigation lateral.

2. A portable sprinkler irrigation system with part-circle sprinklers and adjustable nozzles. Tall risers and tripods are used for tall crops. Pressure regulators are employed on appreciable slopes.

3. Water delivery to the sprinkler line is measured through a Sparling meter.

4. Precipitation is measured by three or four pairs of parallel lines of catch cans. These cans are set above each row. The precipitation received by any one furrow watershed is a mean of 12 or 16 catch-can measurements. The catch cans are set on the ground between plants early in the season. Later in the season they are supported on laths. Tall crops require the use of overhead suspension with two parallel cables holding each row of cans. In any event, the tops of the cans must be level and even with the top growth of the crop.

5. Runoff is measured by means of small Parshall and H_s flumes at the end of each furrow. Hydrographs are obtained by the use of portable water stage recorders on each flume.

6. Velocities are measured by means of salt injection into the furrow runoff streams and then timing the travel of the more highly ionized discharge to successive stations at which meter-connected electrodes are located.

7. Records of furrow cross sections are made before and after storms at selected stations by means of photographing a metal grid pressed into the soil across the furrow.

8. Records of depths of runoff flows are obtained by means of modified water stage recorders at selected stations.

9. Erosion is measured by periodic volumetric sampling of the discharge streams and subsequent drying and weighing of the soil. Particle-size distribution analyses are also made on these soil samples. Similar analyses are made from composite soil surface samples taken from the furrows before and after storms.

10. Wind movement is measured by an anemometer. Wind direction is observed from a weather vane.

11. Water and soil temperatures are measured.

12. Sprinkler pressures are measured with a pitot pressure gage and line pressure is observed at the pump.

13. Furrow profiles are obtained and bench marks set to orient the furrow cross-section photos and depth recorders.

14. Soil moisture samples are obtained to determine moisture contents of the soil before and after irrigation.

RESULTS AND DISCUSSION

Some phases of this study have been more productive than others. For example, measurements of erosion made in 1959 are very useful. Harry Weakly[3] has been responsible for this area of investigation.

Where erosion occurs, the furrow depth recorders sometimes silt-up. We have not been able to correlate velocities obtained by means of salt injection with those computed from discharge and the indicated furrow cross-sectional area. In fact, a high degree of accuracy will be required in our field measurements of furrow flow depth before we can do anything with the parameters involved in the $Q = AV$ relationship. This infers that we have not successfully measured the roughness coefficients in furrow flow, which is true.

Furrow Roughness

The roughness coefficient in furrow flow from rainfall runoff is initially a constant along the entire furrow length, assuming that the furrows are mechanically uniform prior to a storm. After runoff begins, there is a fairly uniform surface flow from the plants in the row toward the furrow. There is also an increased discharge with each downstream station along the furrow just before and after the time of concentration is reached. This means that the roughness coefficient is subject to the direct effect of the runoff and related soil movement from above the wetted perimeter of the furrow. The effect of the discharge stream on furrow roughness will not be uniform along the length of the furrow. It is not anticipated that the individual or combined effects will be linear with elapsed time. It is anticipated that a nearly constant value is approached with a constant discharge.

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[3] Soil Scientist, Soil and Water Conservation Research Division, Agricultural Research Service, U. S. Department of Agriculture, at the University of Nebraska, Lincoln.

The effect of furrow roughness is apparent in considering the velocities measured at successive stations in the furrows. These data are presented in table 1. The velocity of the streams measured was essentially uniform along the length of the furrow on a majority of the furrows. If we consider only the first three farms in the table, on which the row spacings were narrower, the velocities tend to increase at the downstream stations on a majority of the furrows. The hydraulic radius was computed for each station and each flow condition, but the apparent experimental errors discourage comparisons.

TABLE 1.--Furrow runoff velocities at successive stations as measured with salt injection technique

Farm	Crop	Slope	Storm No.	Furrow No.	Velocity Station 1+50	3+00	4+50	6+00
		Percent			Ft./sec.	Ft./sec.	Ft./sec.	Ft./sec.
Stroh	Potatoes	1.5	1	4	0.56	0.63	0.80	0.88
			1	6	.78	.73	.73	.73
			2	4	1.03	1.13	1.29	1.29
					1.01	1.08	1.27	1.30
				6	.92	.90	1.10	1.18
					.96	.95	1.12	1.20
	Sugar beets	1.5	2	6	0.87	0.75	0.74	0.74
					.85	.78	.80	.80
				10	.78	.76	.87	1.02
Lebsack	Corn	2.6	2	3	1.03	1.17	1.51	1.65
					1.15	1.32	1.62	1.72

TABLE 1.--Continued

Farm	Crop	Slope	Storm No.	Furrow No.	Velocity			
					Station			
					1+50	3+00	4+50	6+00
		Percent			Ft./sec.	Ft./sec.	Ft./sec.	Ft./sec.
				6	1.69	1.78	1.93	1.97
					1.61	1.70	1.90	2.00
					1.66	1.75	2.00	2.11
Wolfe	Milo	0.6	1	4	0.85	1.01	1.03	1.03[1]
					.98	1.24	1.15	.97[1]
					Station			
					1+30	2+60	3+90	5+00
Henderson	Corn	1.2	1	4	0.71	0.65	0.66	0.69
					.93	.84	.80	.91
			2		1.18	1.17	1.20	1.20
					1.23	1.25	1.30	1.33
					1.29	1.31	1.35	1.35
				2	.71	.75	.76	.74
					.79	.79	.79	.79
					Station			
					1+50	3+00	4+50	5+80
Geiger	Corn	1.2	1	3	1.32	1.32	1.35	1.35
					1.30	1.33	1.40	1.40
			2		1.30	1.28	1.13	1.02
					1.39	1.35	1.48	1.65
					1.29	1.30	1.37	1.44
				5	1.29	1.34	1.33	1.33
					1.30	1.34	1.46	1.46
					Station			
					1+00	2+00	3+00	3+90
Geiger	Corn	1.8	1	3	1.18	1.23	1.29	1.29
					1.27	1.29	1.32	1.32
				5	.96	1.04	1.03	1.03
					.95	.95	.99	1.03

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[1] Station 5+50.

TABLE 1.--Continued

Farm	Crop	Slope	Storm No.	Furrow No.	Velocity Station 1+00	2+00	3+00	3+90
		Percent			Ft./sec.	Ft./sec.	Ft./sec.	Ft./sec.
Geiger	Corn		2	3	1.35	1.41	1.40	1.37
					1.37	1.44	1.42	1.39
					1.40	1.46	1.45	1.42
				5	.84	.90	.86	.84
					.98	1.04	.94	.98

Flow Velocity

The measured furrow velocities are compared with their respective furrow discharges in figure 1. On any one crop-slope site the velocities are generally higher with increased rates of runoff. In some cases increased velocities have been due in part to elapsed storm time and the total volume of water previously discharged through the furrow. The highest velocities were measured on the steepest furrow slope. The furrows with the least slope also developed comparatively high velocities with high runoff rates. This indicates the effect of decreasing the hydraulic radius.

Figure 2 shows the relationship of elapsed time and discharge to the average furrow velocity. This figure is typical of the data similarly plotted for other fields. Changes in the roughness coefficient that would materially affect the furrow velocity are apparently complete by the time the storm runoff reaches a peak in the furrow.

Furrow Detention

A number of factors affect the amount of water stored in the furrow at the end of a storm. Length, furrow cross section, and slope are important in this respect but are constants for any one experimental site. A linear relationship was found to exist between furrow detention (L^3) and the runoff rate at the end of the storm (L^3T^{-1}). The furrow detention was obtained from the total runoff occurring after the storm. Some infiltration takes place during the time required for drainage of the furrow, but it is assumed that this is of minor importance.

Figure 3 is a typical plot of furrow detention compared to the end of the storm runoff rate. A quick survey of the data at hand shows that a rule of thumb procedure might be used for similar conditions. Furrow detention in gallons equals 4 to 5 times end of the storm discharge in gallons per minute.

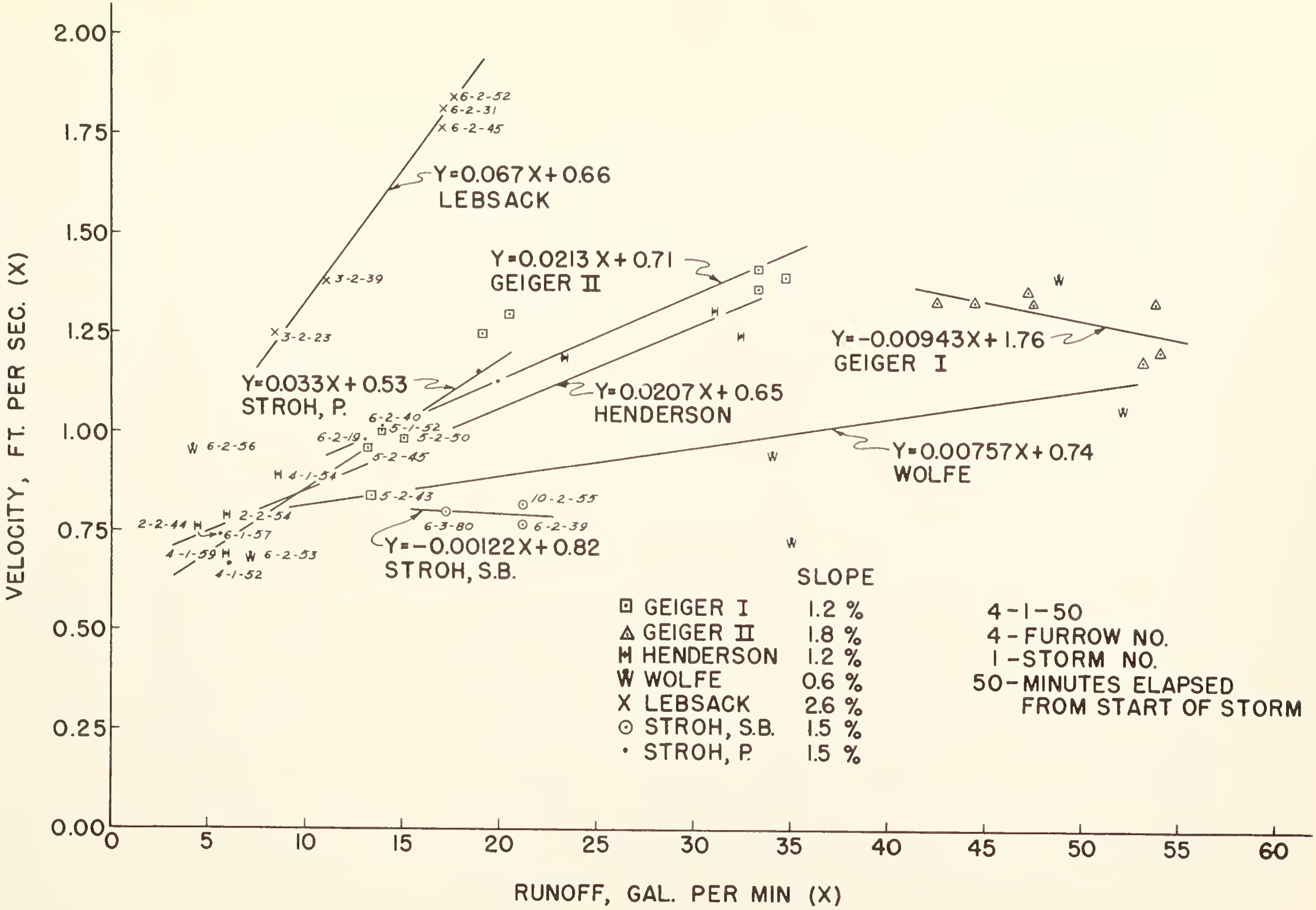

Figure 1.--Distribution of furrow velocities and runoff rates 1959 studies.

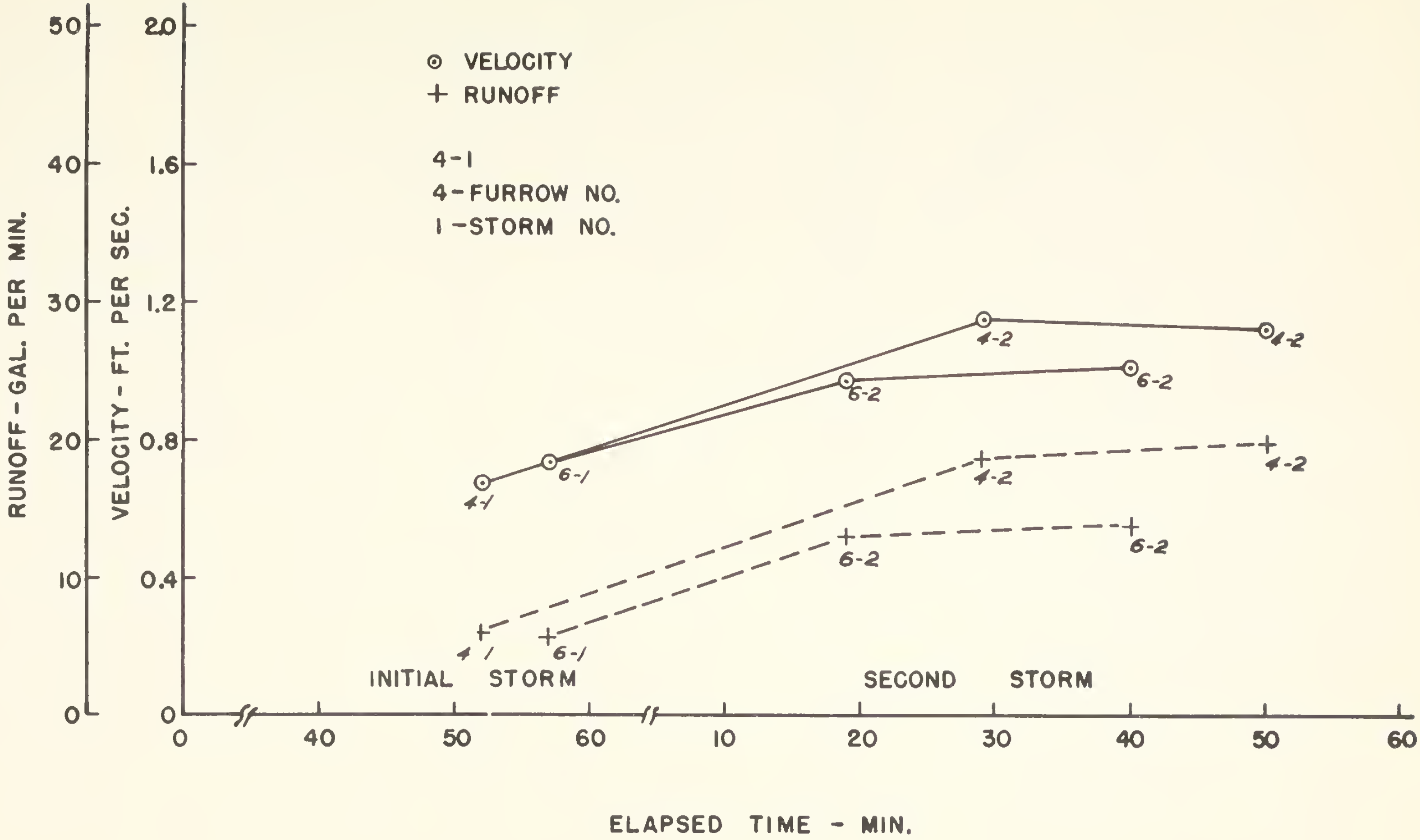

Figure 2.--Average velocity for furrow and furrow runoff with elapsed storm time, 1.5% slope, Stroh farm, Johnstown, Colorado, July 2-3-4, 1959, 36-inch furrow spacing, potatoes.

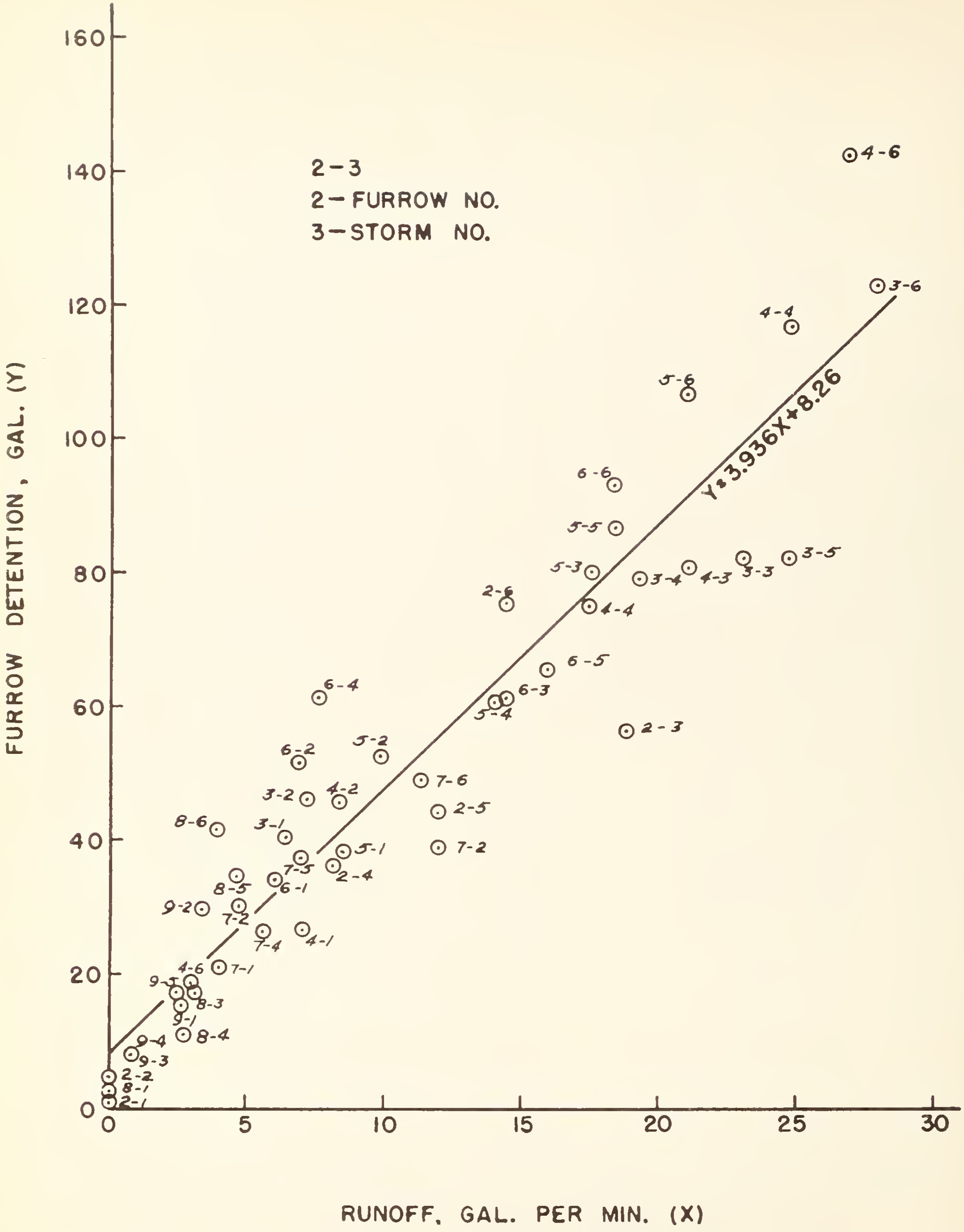

Figure 3.--Furrow detention compared with runoff rate (end of storm), potatoes, Stroh farm, Johnstown, Colorado, July 2-3-4, 1959, 1.6% slope, 600 ft. run.

Further analyses will provide a mathematical relationship based on rainfall intensity, intake rate, furrow slope, cross section, and length.

Runoff

Hydrographs of runoff were obtained from water stage recorders mounted on the flumes measuring the runoff. These were reduced to linear hydrographs using the individual flume calibrations.

Intake rate curves were plotted from the hydrographs. While this information is valuable, no attempt will be made to present it here. A few comments should be included, however. Differences in rainfall intensity between furrows did not create primary variations in intake rates. Some furrows had particularly high or low intake rates through both the initial and antecedent moisture condition storms. This was attributed to a furrow's lack of tractor tire traffic or to the effect of such traffic.

Erosion

Erosion measurements were made from volumetric discharge samples. The rate of erosion is an exponential function of the simulated rainfall intensity. Figure 4 is an example of the distribution of the rate of erosion with rainfall intensities.

Two striking characteristics were evident on a number of the sets of erosion data plotted. Not only does the rate of erosion increase rapidly with increased rainfall intensity, but very little time is required to produce the high rate of soil loss. Two of the highest soil loss values shown in figure 4 were measured 7 minutes after the start of the third storm. On this particular field, a heavy canopy of nearly mature corn prevented water from falling directly upon the soil.

Particle size distribution analyses of the soil samples and erosion samples obtained are not yet complete. Even with the crop canopy there appears to be a sorting action in the soil with the erosion process.

Weakly found that less than 60 percent of the total soil particles contributed over 90 percent of the material removed in runoff from a Tripp fine sandy loam on the Scotts Bluff Experiment Station. The erosion was produced from newly-furrowed young sugar beets on a field with an average slope of 2 percent. Practically all of the eroded material fell in particle sizes below 50 microns and would remain in suspension with very little agitation. Particle size analyses of the top one-eighth inch of the soil surface following the "storms" indicated increased percentages of sand grade particles.

Time of Concentration

This study has provided excellent opportunities for studies of the time of concentration. The initial storm duration of 60 minutes has been adequate

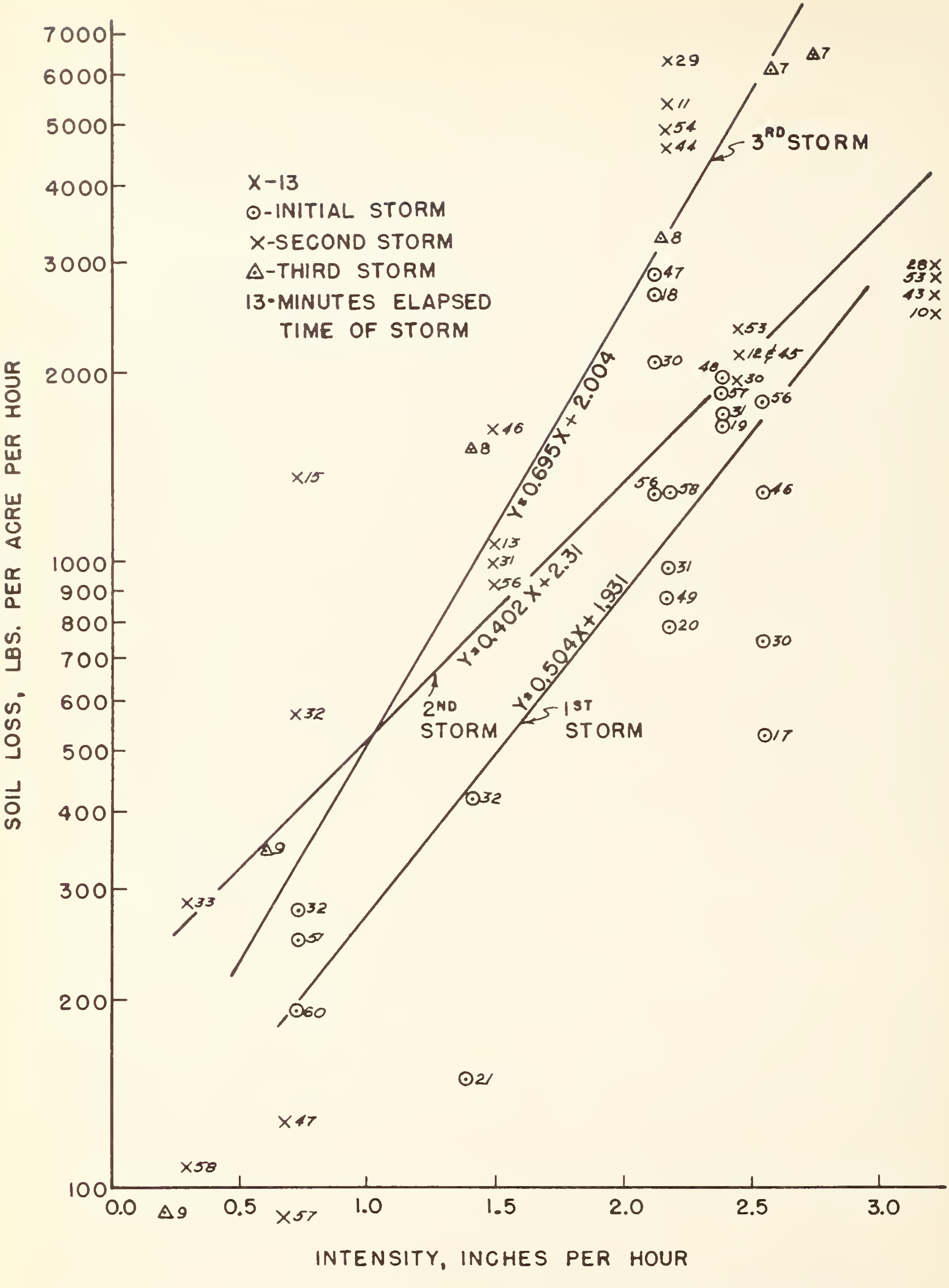

Figure 4.--Rates of erosion measured with various simulated rainfall intensities. Corn, 40-inch rows, 1.8% slope, 400-foot runs, Geiger Farm, Seward, Nebr., August 24-25, 1959, Sharpsburg Silt Loam.

to provide near peak runoff for the particular storm intensity. A total for four storms was employed and four hydrographs were obtained for each furrow. Since hydrographs were also obtained for a number of furrows on each field site, replication was obtained with storm intensity being the variable.

A few comparisons of the time of concentration observed with times of concentration computed by empirical methods have been made.

The rational method of solving for the time of concentration provided comparable values. This equation is:

$$T_c = 0.0078K^{0.770}$$

where $K = \frac{L}{S^{\frac{1}{2}}} = L^{3/2}H^{-\frac{1}{2}}$

and L = Maximum length of travel in feet

H = Difference in elevation between most remote point and outlet in feet

S = Slope, $\frac{H}{L}$

Of more interest to Soil Conservation Service personnel is the equation[4/]

$$T_c = \frac{0.71}{b}$$

where $b = \frac{\log q_1 - \log q_2}{t_2 - t_1}$

In this equation, b is the slope of the semilogarithmic plot of the falling limb of the hydrograph. The times are reversed in the equation to provide a positive number. The times of concentration computed from this equation are also comparable to the observed values.

The magnitude of the differences in the observed short times of concentration and computed values is often large. A part of the variation can be ascribed to experimental error. We believe that statistical analyses will attach significance to the influence of the precipitation intensity and the runoff discharge at the end of the storm. Comparatively large times of concentration have been observed at the end of the first storm in conjunction with relatively low runoffs.

The time of concentration as obtained from the hydrographs has been taken as the elapsed time between the inflection points on the upper and lower ends

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[4/] U. S. Department of Agriculture - Soil Conservation Service Engineering Handbook, Supplement A, Section 4, Hydrology, pp. 3.15-1 and 3.15-2.

of the falling limb of the hydrograph. Time has been plotted on a linear abscissa and discharge on a logarithmic ordinate for all of the falling limbs. This provided a straight line between the inflection points and permitted a direct reading of the slope. It has the disadvantage, however, of incorporating two additional opportunities for errors in transposition from the water stage recorder chart to a linear hydrograph and then to the semilogarithmic plot. Comparisons were made of observed times, and we concluded that more reliable values could be taken directly from the recorder charts.

The mean values of the times of concentration observed with various furrow slopes, lengths, and spacings are presented in table 2. These values may be useful for comparison with results obtained from empirical equations until such time as an equation based on data from furrow-irrigated fields may be presented.

TABLE 2.--Times of concentration (mean values) observed for furrows with various slopes, lengths, and spacings

Slope	Length	Row spacing	Time of concentration	Crop and farm
Percent	Feet	Inches	Minutes	
0.06	400	36	11	(Milo-S.B. SCS)
.14	400	22	10	(Beans)
.2	400	22	11	(Sugar beets)
.4	600	40	18	(Milo-Hartman)
.7	500	40	19	(Milo-Hartman)
.6	600	40	10	(Milo-Wolfe)
1.2	400	22	8	(Sugar beets - S.B.)
1.2	600	40	10	(Corn)
1.2	520	39	8	(Corn-Henderson)
1.2	600	40	8	(Corn-Geiger)
1.8	400	40	7	(Corn-Geiger)
1.5	600	22	8	(Sugar beets-Stroh)
1.5	600	36	9	(Potatoes-Stroh)
2.3	600	22	8	(Sugar beets - S.B.)
2.3	600	22	7	(Sugar beets - S.B.)
2.6	600	36	5	(Corn-Lebsack)

THE DESIGN OF FURROW IRRIGATION SYSTEMS [1]

by

W. C. Little [2]

INTRODUCTION

Furrow irrigation may offer many benefits as compared with sprinkler irrigation, such as lower pumping and labor costs, and in some cases more uniform water distribution. However, these are recognized only by proper design. Poor design may lead to waste of water and/or inadequate irrigation and soil erosion. Previous designs have relied upon data compiled through local experience obtained by field trials and may be used only in those areas [3] [4]. This type of design serves only as a general guide, which necessitates an evaluation of the system after installation. Hence, the need was presented to develop a method or procedure to design furrow irrigation systems prior to land forming. Due to the many variables involved in the design of furrow irrigation systems, many of these variables must be eliminated by assuming them to be constant throughout the procedure. Otherwise, the approach to be presented would be too complex to attempt developing. However, once the procedure has been refined sufficiently, the significance of these terms can be considered. The author realizes that many of these variables will greatly affect the design of a system, but it is the intent of this paper to present the basic method, which, with further refinements, may enable a furrow irrigation system to be designed prior to any land forming.

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[1] Contribution from Soil and Water Conservation Research Division, Agricultural Research Service, U. S. Department of Agriculture in cooperation with the Alabama Agricultural Experiment Station, Auburn University, Auburn, Alabama.

[2] Agricultural Engineer, Eastern Soil and Water Management Research Branch, Soil and Water Conservation Research Division, Agricultural Research Service, U. S. Department of Agriculture.

[3] Criddle, W. D., Davis, S., Pair, C. H., and Shockley, D. G. Methods for evaluating irrigation systems. U.S.D.A. Agriculture Handbook No. 82, 1956.

[4] Quackenbush, T. H., Renfro, G. M., Beauchamp, K. H., Lawhon, L. F., Eley, G. W. Conservation irrigation in humid areas. U.S.D.A. Agriculture Handbook No. 107. 1957.

NOMENCLATURE

$Q_o, Q_1, \ldots Q_n$ = Flow rate, in gallons per minute (g.p.m.) at the beginning of a reach (length in feet of sections of row).

$W_o, W_1, \ldots W_n$ = Stream width, in inches, at the beginning of a reach.

$t_1, t_2, \ldots t_m$ = Increments of time in minutes.

$I_{1,1}, I_{1,2}, \ldots I_{1,m}$ = Average furrow intake rate in g.p.m. per foot of row for reach 1 during time intervals $t_1, t_2, \ldots t_m$.

L = Total length of row in feet.

$l_1, l_2, \ldots l_n$ = Length of reach 1, 2,....n, in feet (where $\Sigma (l_1, l_2, \ldots l_n) = L$)

$v_{s_{1,1}}, v_{s_{1,2}} \ldots v_{s_{1,m}}$ = Storage volume in gallons for reach 1 during time increments $t_1, t_2 \ldots t_m$, respectively.

$V_{s_1}, V_{s_2} \ldots V_{s_n}$ = Total storage volume in gallons for reach 1,2....n

$v_{I_{1,1}}, v_{I_{1,2}} \ldots v_{I_{1,m}}$ = Infiltrated volume in gallons for reach 1 during time increments $t_1, t_2 \ldots t_m$, respectively.

$V_{I_1}, V_{I_2} \ldots V_{I_n}$ = Accumulative infiltration volume in gallons for reach 1,2....n

DESIGN CONSIDERATIONS AND CRITERIA

In order to simplify the design procedure at present, the design criteria as described by Hall [5] will be used. In addition, other factors must be considered.

Since many factors will seemingly be ignored in the procedure, a brief discussion of the effects of these factors upon the design seems in order. Furrow cross-sectional area plays a most important role in the design, especially while the water is advancing. Furrow cross section, for a given slope, determines the stream width produced for a given stream size. Furrow cross section consequently governs the stream width and surface storage volume in the furrow for a given slope. For this study, however, only one furrow cross section is used. The furrow cross section is V-shaped with 1 to 5 side slope and a slightly rounded bottom. Figure 1 was obtained by forming a furrow (same furrow cross section as on furrow irrigation system used for evaluation) on the contour and applying several stream sizes and measuring the stream width

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[5] Hall, Warren A. Estimating irrigation border flow. Agr. Engin. 37: 263-265. 1956.

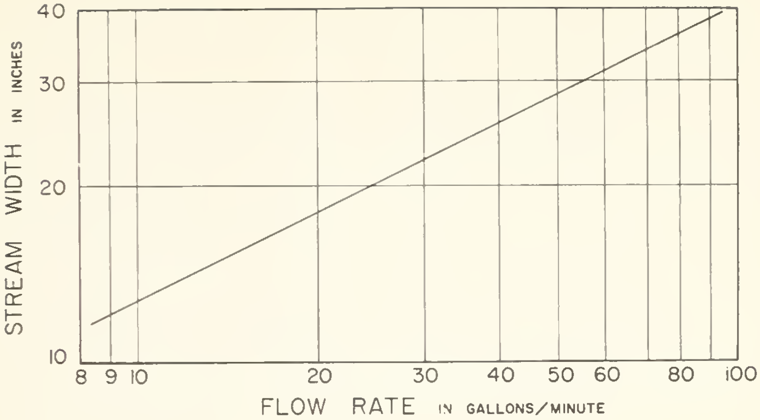

Figure 1.--Relationship of flow rate versus stream width.

produced. This is necessary because the field has not been leveled and other furrow systems in the area would not likely give similar results. Figure 1 was obtained on Decatur fine sandy loam and can be used only for this soil. Similar relationships must be established for other soils. Also, this relationship (figure 1) can only be the relationship which exists at the time of measurement because of the changing soil conditions. It is evident that the furrow roughness will change throughout the growing season, which will change this relationship. However, it is not the intent of this paper to evaluate these effects but to use these basic relationships in developing a procedure to design furrow irrigation systems. Myers [6] points out the need for more studies on the mechanics of surface flow.

Furrow intake rate was obtained by methods developed by Bondurant [7] (figure 2). In this study, stream widths of 10, 20, and 30 inches were used. The relationship will change throughout the irrigation season, due to many factors [8] [9] [10]. The furrow intake rate will change also, due to the land forming operation. The magnitude of these variables is not known but should be evaluated.

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[6] Myers, Lloyd E., Jr. Flow regimes in surface irrigation. Agr. Engin. 40:676-677, 682-683. 1959.

[7] Bondurant, James A. Developing a furrow infiltrometer. Agr. Engin. 38:602-604. 1957.

[8] Lewis, M. R., and Powers, W. L. Study of the factors affecting infiltration. Soil Sci. Soc. Amer. Proc. 3:334. 1938.

[9] Philip, J. R, The theory of infiltration: 6 Effects of water depth over soil. Soil Sci. 85:278-286. 1958.

[10] Schiff, L. The effect of surface head on infiltration rates based on the performance of ring infiltrometers and ponds. Amer. Geophys. Union Trans. 34:257,266. 1953.

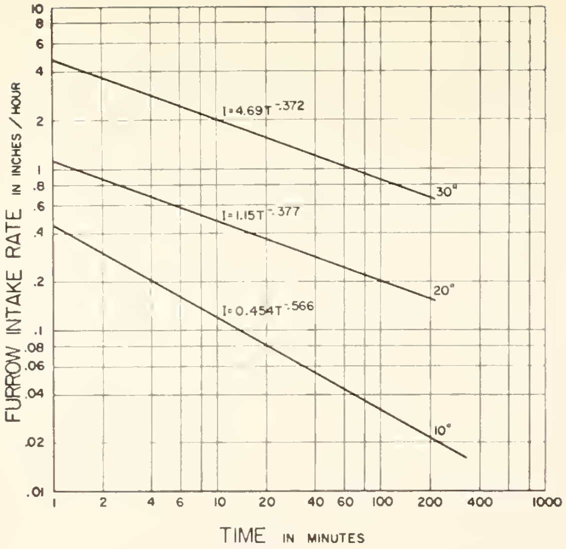

Figure 2.--Relationship of furrow intake rate versus time for stream widths of 10, 20, and 30 inches (40-inch row spacing).

Furrow irrigation is a flow process which is both nonuniform (changes with distance) and unsteady (changes with time). In the design procedure, constant time intervals are used to calculate the rate of advance. The lengths computed by using short time intervals will allow the flow in each length and time interval to be considered uniform and steady. The time intervals found most convenient for computations are 5-minute intervals from 0 to 60 minutes; 10-minute intervals from 60 to 100 minutes; and then 50-minute intervals until the basic intake rate is reached. This selection of time intervals was based upon the decrease in furrow intake rate with time. Longer time intervals may be used when the intake rate decreases or reaches a near steady state.

DESIGN PROCEDURE

Four different stream sizes were assumed and the efficiency and running time calculated for each. The maximum stream size to be assumed is the maximum permissible stream size, as defined in the Engineering Handbook [11], which is $Q = \frac{10}{s}$, where Q is flow rate in g.p.m. and s is the slope in percent. The other stream sizes are selected in 10-g.p.m. intervals below the maximum. The optimum stream size can then be determined from the efficiency and uniformity of application after the calculations for each are completed.

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[11] Engineering and Watershed Planning Unit. U. S. Department of Agriculture, Soil Conservation Service. Instructions and criteria for preparation of irrigation guides. Engineering Handbook Section 15, Part 1, Far Western States and Territories. 1957.

The rate of advance is calculated by choosing equal intervals of time for the water to advance. This will cause the lengths for each reach to be increasingly smaller but affords the advantage of requiring only one I = f(w,t) graph with equal time intervals when the intake rate is changing rapidly.

The distance the front will advance during the first time interval, t_1, is a function of the following quantities and is related by:

$$Q_o t_1 = v_{s_{1,1}} + v_{I_{1,1}}$$

where $v_{s_{1,1}}$ = surface storage volume for first reach during first time interval.

$v_{I_{1,1}}$ = volume infiltrated for first reach during time interval t_1.

but

$$v_{s_{1,1}} = 0.75 \times 7.48 \times A_o l_1$$

where 0.75 = a constant describing the water surface configuration during the advance of the water down the furrow.

7.48 = cubic feet per gallon.

A_o = area produced by stream width, W_o, corresponding to Q_o.

l_1 = length of reach 1.

and

$$v_{I_{1,1}} = I_{1,1} t_1 l_1$$

where $I_{1,1}$ = determined as follows:

From Q_o, the corresponding width, W_o, is read from the Q = f(w,s) graph. W_o is the stream width at the end of the time interval where the stream width at the beginning was zero.

Therefore, the average width is $\frac{0 + W_o}{2}$ or $\frac{W_o}{2}$ during the time interval. From the I = f(w,t) graph, $I_{1,1}$ corresponding to $\frac{W_o}{2}$ would be read for the first time interval.

From the foregoing we know the following quantities:

$A_o, I_{1,1}t_1$, and Q_o

From which l_1 can be computed by the relationship

$$l_1 = \frac{Q_o t_1}{0.75 \times 7.48 A_o + I_{1,1}t_1}$$

Now that $v_{s_{1,1}}$, and $v_{I_{1,1}}$ are known, l_2 can be computed by the same procedure

$$2Q_o t_2 = v_{s_{1,1}} + v_{I_{1,1}} + v_{s_{2,1}} + v_{I_{2,1}}$$

where: $v_{s_{2,1}}$ = surface storage volume for second reach during first time interval

$v_{I_{2,1}}$ = volume infiltrated for second reach during first time interval

This procedure is used to compute the length of each reach until the cumulative length, L, is the actual row length. Computations for the volume infiltrated for each reach are continued until the cumulative infiltration volume, V_{I_n}, is the desired amount of application. From the cumulative infiltration volume for each reach, V_{I_n}, a graph may be constructed of the depth of application as ordinate versus distance down the furrow as abscissa. This graph shows the depth of application from which the amount of deep seepage can be determined. From the flow rate for the end of the last reach, the amount of runoff is determined. The efficiency, for this stream size, is then calculated.

RESULTS AND DISCUSSION

The rates of advance were calculated using figures 1 and 2 for stream sizes of 20, 30, 40, and 50 g.p.m. per furrow. The results are shown in figure 3. From figure 3, it can be seen that the calculated rate of advance is almost the same for all stream sizes, which is not the actual case in the field. This discrepancy may be due to several factors: (a) For the small stream sizes, the stream width produced is small, which causes a decrease in the intake rate, and also a decrease in storage volume; (b) for the large stream sizes, the stream width produced is large, which causes an increase in the intake rate and also an increase in the volume of storage. Consequently, the rates of advance for all stream sizes, as calculated, are approximately the same.

Another factor which is sure to contribute to the great differences between the calculated and measured rates of advance is the field surface irregularities. This method of calculating the rate of advance has no provisions for compensating for the additional surface storage volume caused by low pockets and nonuniform slopes. It is the opinion of the investigator that

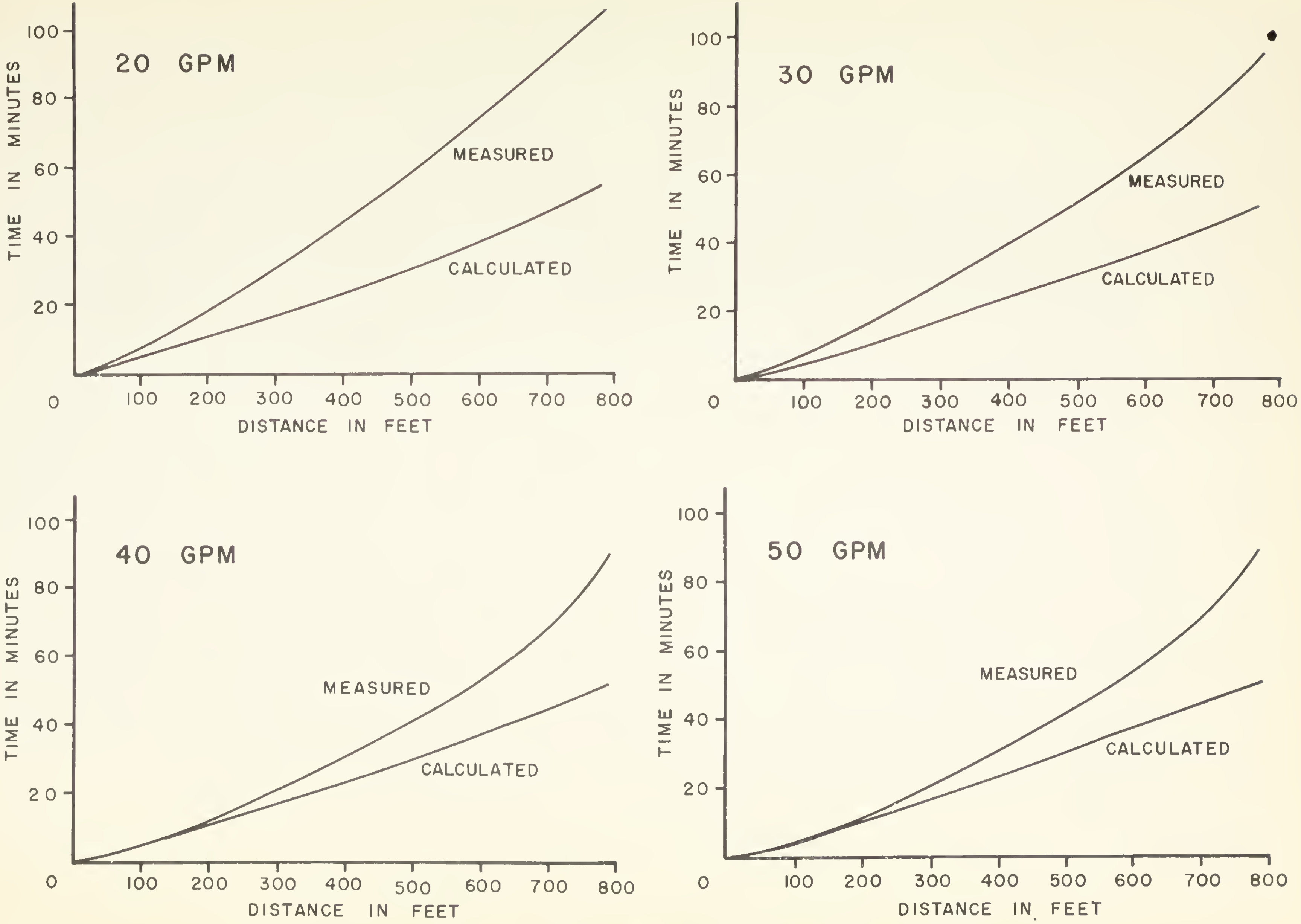

Figure 3.--Relationship of measured and calculated rate of advance.

the additional surface storage volume has a much greater effect on the rate of advance than all of the infiltration parameters combined.

The discrepancies occurring between the calculated and measured results are obvious but cannot be satisfactorily explained. The investigator has discussed this paper with others who have attempted this same procedure but who were also unable to formulate a workable solution. As a result, their work was never published.

Before making further refinements, much work must be performed to determine the flow characteristics in furrows along with studies to validate the assumptions made in the procedure.

SUMMARY

The procedure presented depends upon empirically derived relationships. Hence, the procedure is no better than the field data obtained. With reliable data, the procedure should afford an estimate of the stream size and running time for a furrow irrigation system prior to land forming.

At present, knowledge of the hydraulic characteristics of flow in furrows is limited. This, alone, does not permit the immediate use of the procedure; consequently, more studies must be performed in order to determine the validity of the procedure, since these conclusions are derived from one year's data. However, before proceeding to make further refinements of the procedure, a study should be initiated to determine the flow characteristics in furrows. This would allow the procedure to be used with more reliability.

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